

## **HAT Cycle Technology Development Program**

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### **Introduction**

The overall goal of the program is to fill technical data gaps in the development of the Humid Air Turbine (HAT) cycle by identifying a combustor configuration that will efficiently burn high moisture, high pressure gaseous fuels with low emissions. The major emphasis is on development of kinetic data, computer modeling, and evaluations of combustor configurations. The intent is that by the end of the program the combustor can be scaled up to test rigs using full scale nozzles. Significant testing is to be performed at the Federal Energy Technology (FETC) facility in Morgantown, WV by in-house FETC personnel.

The work covered in this report is on the two tasks that have been the main focus during the first year of the program, Kinetic Modeling and Fundamental Data Base Generation, and FETC Combustion Evaluation Studies.

### **Task 201: Kinetic Modeling and Fundamental Data Base Generation**

#### Objectives

The objectives of this task are to conduct laboratory experiments and undertake kinetic modeling studies to define the effects of high water vapor content in air on the flame stability and emissions in HAT cycle combustion systems burning natural gas. The effects of temperature, pressure, fuel composition, and H<sub>2</sub>O content on CO, NO<sub>x</sub>, and UHC production, flame stability, and ignition will be defined. Kinetic mechanisms will be evaluated and modified as necessary to accurately describe the experimental results. Validated kinetic mechanisms will be evolved into reduced reaction sets for integration into CFD codes. Ultimately, the results of the small scale combustion experiments and kinetic modeling will be used to guide in the design of a full scale nozzle and combustor.

### Definition of Tasks

The tasks which are to be performed in the small-scale combustor evaluation program are divided into the following phases:

Modify test combustor facility and flow systems to accommodate steam injection.

Perform baseline combustion tests to determine operating limits of HAT cycle combustor with existing facility design.

Design laminar premixed or partially premixed turbulent burner to provide optimum flame stability and minimized emissions under HAT cycle conditions.

Perform extensive combustion tests to determine in detail the effects of temperature, pressure, fuel composition, and H<sub>2</sub>O content on emissions and operability limits of HAT cycle combustor.

Perform data analysis and develop design criteria for sub scale combustor testing in sector rig.

Part of Task 201 is devoted to examining the chemical kinetics of NO<sub>x</sub> production, CO burnout, and unburned hydrocarbon emissions. For this program, UTRC is utilizing computer codes for chemical kinetic predictions based principally upon CHEMKIN II, one of the best chemical kinetic tools for examining this problem since the code readily treats pressure-dependent variations in reaction rates. Conditions up to 60 atmospheres pressure are of interest to this program and existing reaction sets will necessarily have to be extrapolated well outside of their validated regimes; hence, the pressure dependent features of CHEMKIN II should minimize related uncertainties. Several kinetic codes interacting with the CHEMKIN II software have been developed at UTRC including a parallel/series network of perfectly stirred reactors for simulation of combustors and predictions of emissions.

### High Pressure Flat Flame Burner Facility

Preliminary tests were performed as part of an evaluation of the applicability of the high pressure flat-flame combustor to this program. This combustor presently is configured to operate with a fully premixed burner at pressures up to 63 atmospheres and inlet temperatures up to 670K (1210R). Tests were performed at a constant inlet equivalence ratio to determine the radial temperature and species profiles at elevated pressures with ambient temperature inlet gas. These tests were to confirm the one-dimensional behavior of the premixed flat-flame burner, shown in Figure 201-1. The probe for obtaining gas samples or thermocouple measurements can be moved radially and the burner translated axially to obtain radial or axial temperature and species measurements. The schematic diagram of the combustion facility showing probe locations is shown in Figure 201-2.



Figure 201-1. Flat Flame Burner Assembly

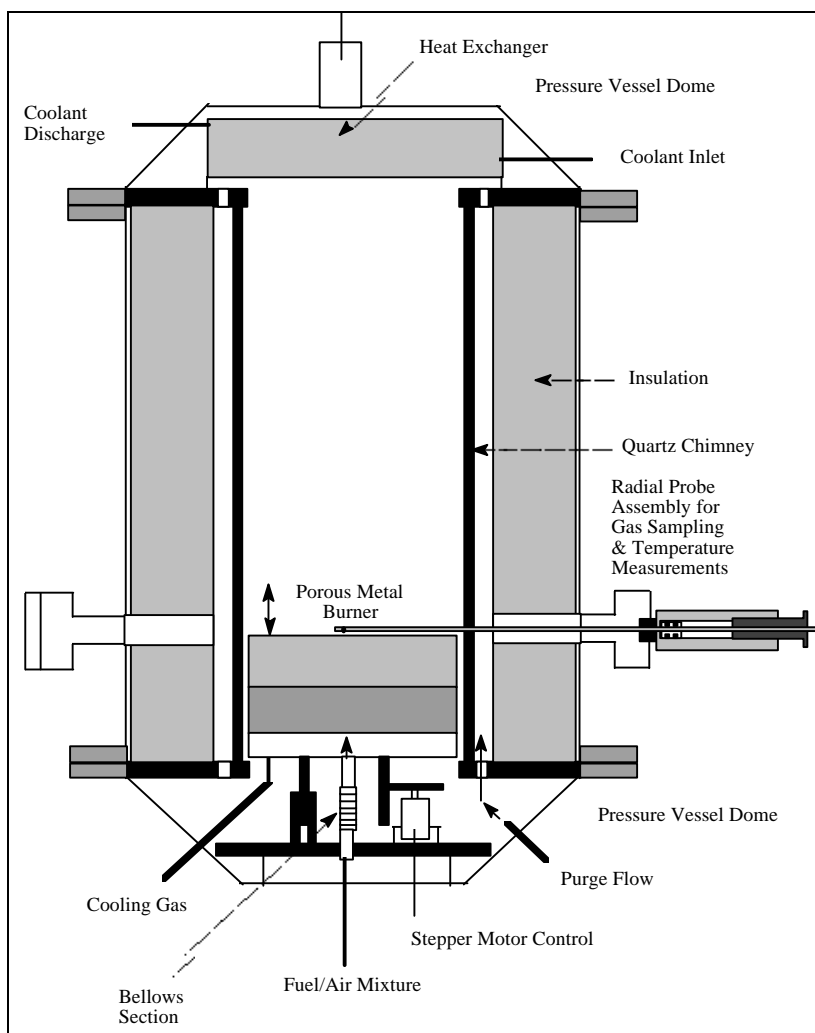


Figure 201-2. Schematic of High Pressure Flat Flame Burner Combustor

A photograph of the flat flame combustion facility is shown in Figure 201-3. The vessel is rated for operation at 63 atmospheres pressure with an inlet temperature of 673K. For the flat-flame combustor evaluation tests, a beryllium/yttrium oxide coated fine wire Type R thermocouple was used to measure the axial (downstream) profile on the burner centerline as a function of vessel pressure. Radial profiles were also acquired at 5 and 10 atm and 5.6mm above the burner surface (the location chosen as well downstream of the flame zone where high gradients would exist in species and temperature). Temperature measurements were also made  $\phi = 0.98$  and  $\phi = 1.3$ . A plot of the radiation corrected radial temperatures at 5 atm are shown in Fig. 201-4 (zero being the midpoint of the burner).

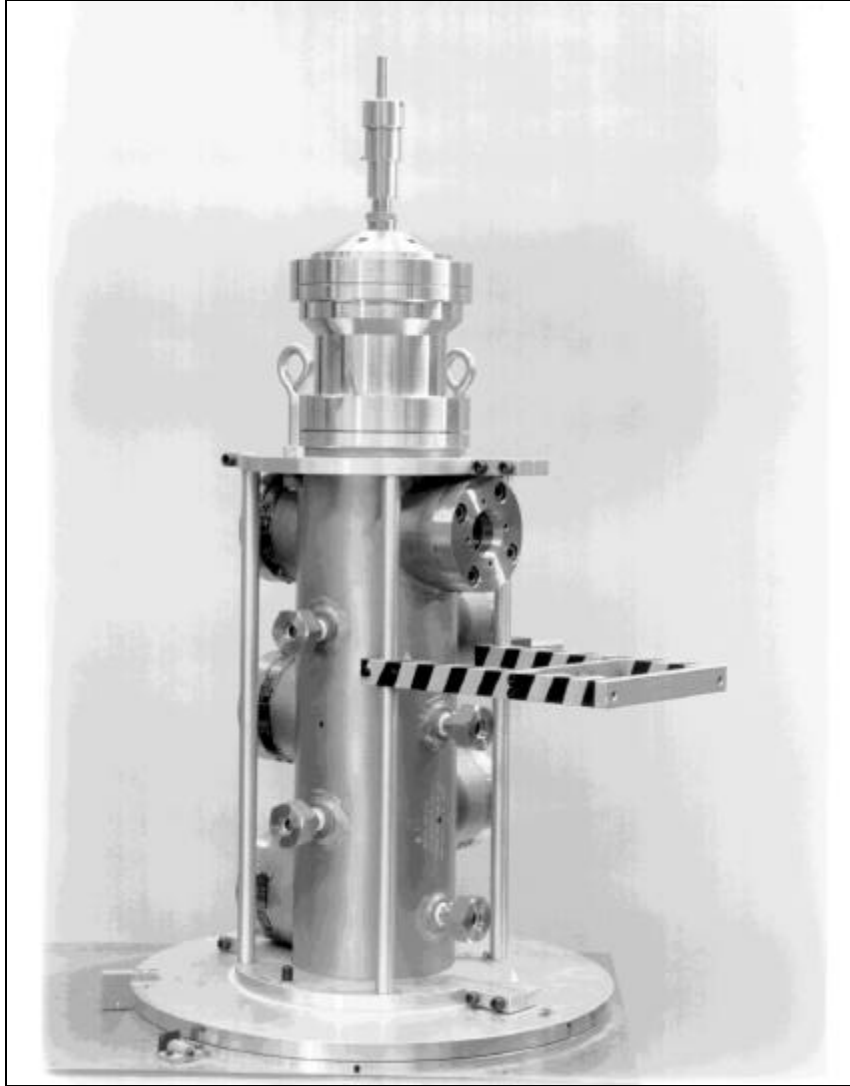


Figure 201-3. High Pressure Flat Flame Combustor

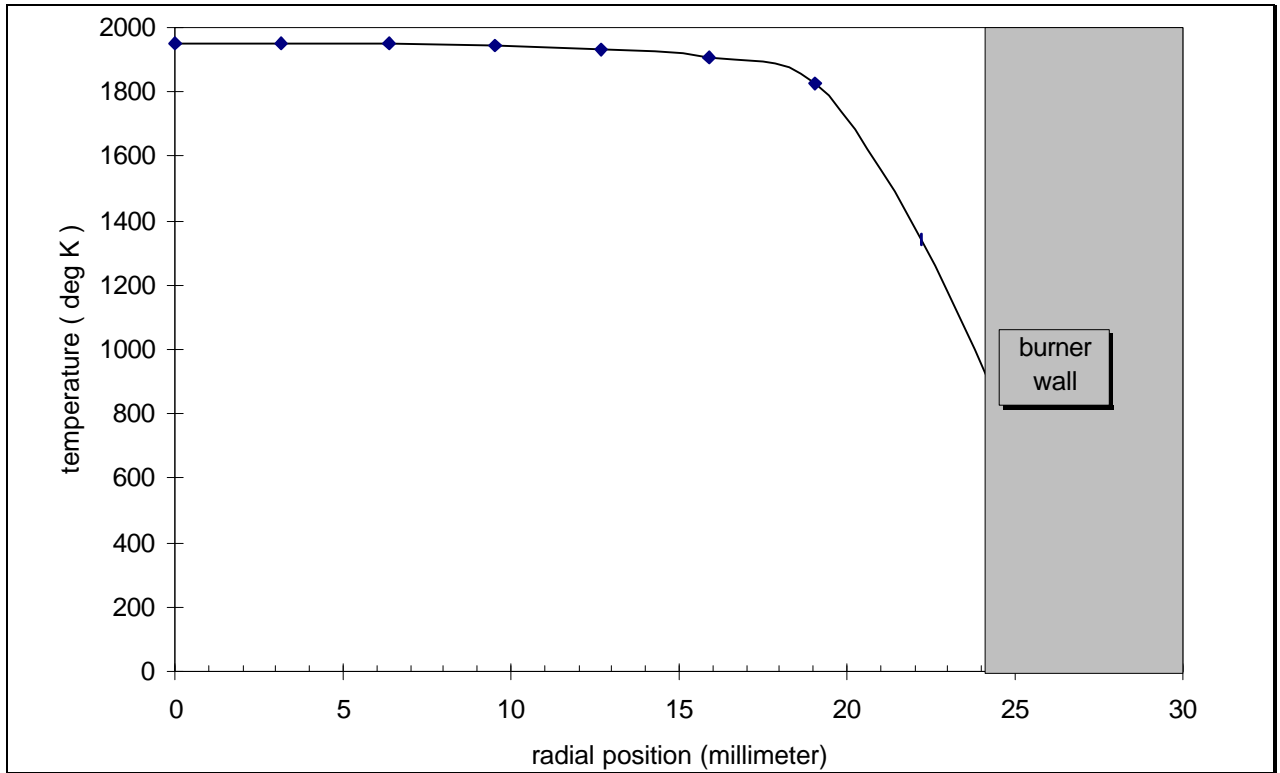


Figure 201-4. Radial temperature profile at 5 atm and  $\phi = 1.3$

These data confirmed the one-dimensional nature of the flat-flame burner which is critical for modeling of this flame structure. However, the laminar flat-flame burner used in this evaluation was not conducive to detailed flame probing at adiabatic conditions. The delicate balance between flame speed and approach velocity to the burner surface in order to position the flame front at precisely the same standoff distance from the burner was very difficult to maintain. Although data was acquired up to 60 atmospheres pressure at an equivalence ratio of 0.95, the radial and axial temperature profiles indicated that the heat loss to the water cooled sintered metal burner varied with pressure. This is shown in Figure 201-5 where it is seen that as the pressure increased, the heat loss to the burner and chimney walls increased. Attempts to lift the flame off of the burner surface to reduce the heat loss only resulted in loss of the flame (ltoff). For this reason, it was decided to concentrate the data acquisition in the high pressure, high temperature turbulent partially premixed flame facility.

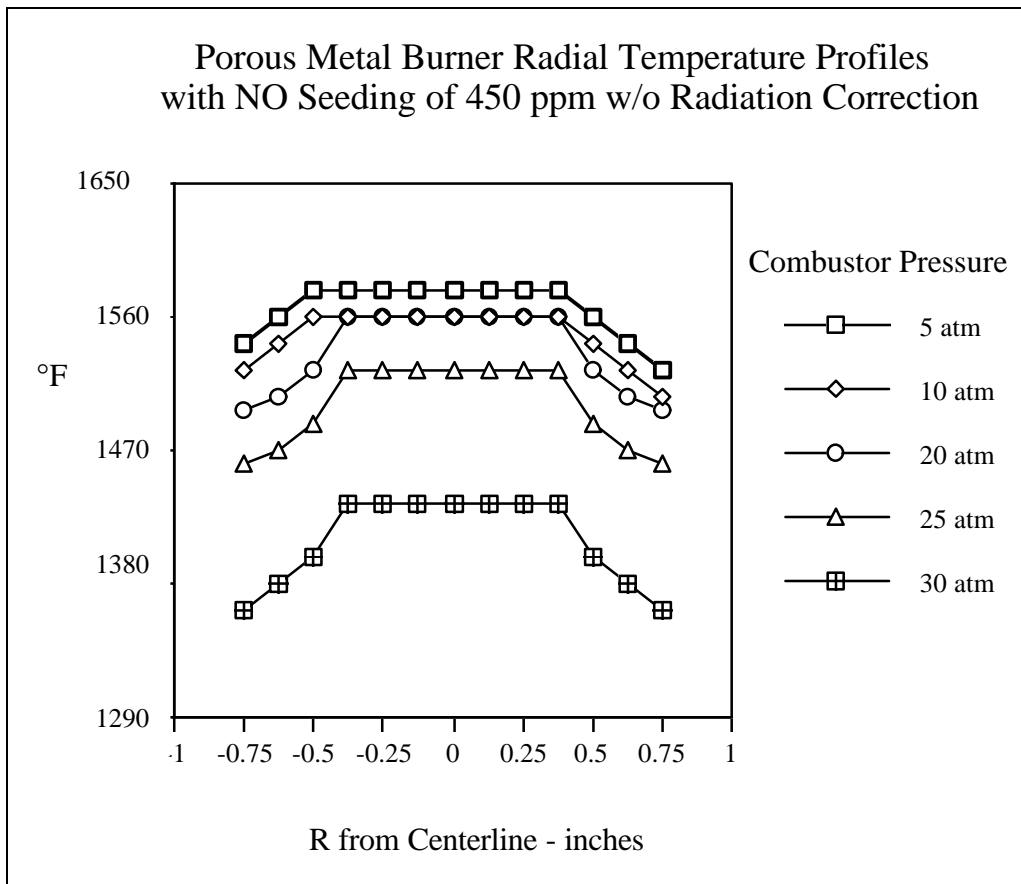


Figure 201-5. Radial Temperature Profiles in Flat Flame Burner at Various Pressures

#### High Pressure, High Temperature Turbulent Burner Facility

The high pressure experimental apparatus designed for this program is composed of 5 subsystems: (1) gas flow control, (2) gas and facility thermal control (heaters), (3) fuel/air mixing section (4) combustor section, and (5) gas analysis system. The fuel-air-water mixture is burned in a combustor where the flame is stabilized by either a porous steel disk or a partially premixed burner configuration. The combustor schematic is shown in Figure 201-6. The flameholder is designed to minimize quenching due to heat loss, and yet provide a stable flame over a wide range of operating conditions, i.e., velocity, equivalence ratio, pressure, and temperature. Testing at conditions expected in a land-based gas turbine enables a comparison to be made between the emissions and flame stability of methane flames with and without water addition.

Initial experiments have been performed at a maximum inlet pressure of 426 psig. All gases for the experiment as well as the inlet section to the combustor are electrically heated to the specified operating temperatures using ceramic lined heating furnaces powered by micro-processor based thermal controllers. The gases were supplied from compressed gas cylinders, monitored and controlled by digital electronic flow meters, and pressure in the reactor controlled with a pneumatically operated back-pressure regulator.

A pressure relief vent was incorporated in the design to prevent rig pressure from exceeding the design value of the pressure vessel. Stress analysis has been performed on each component of the system and the reactor components pressure tested by the manufacturer to comply with standard pressure vessel codes for operation at the design temperature and pressure.

Gas sampling can be accomplished through the use of 3 probes; one located just downstream of the mixing zone, one fixed probe located in the combustor exhaust stream, and one axially-oriented probe which can be positioned along the axis of the combustor. The data presented below were obtained from the fixed sample port located in the combustor exhaust. The traversing probes are cooled with water heated to 125° C to prevent internal water condensation. The position is adjustable on the traversing probes through rotating a threaded collar which retains the probe in a fixed mount which in turn is threaded into the desired probe location in the apparatus. The gas sample is conducted to the analyzers through a heated sample line and water trap as required. Temperature is monitored at six locations in the apparatus with chromel-alumel thermocouples whose outputs are displayed on digital panel meters. In the combustor, the temperatures are monitored by two Type B thermocouples (Platinum-30% Rhodium versus Platinum-6% Rhodium). The viewport is monitored by a video camera so that personnel are not positioned in direct line-of-sight with the viewport. The viewport is located at the flame-holder in the combustor section, 90° from the position of the hot surface platinum wire ignition source. The gas sampling system includes two NDIR CO and one NDIR CO<sub>2</sub> analyzer, a paramagnetic O<sub>2</sub> analyzer, and a Thermo-Electron NO-NO<sub>2</sub>-NO<sub>x</sub> analyzer. The gas sample is transported to the emissions instrument rack through a metal-bellows sample pump. Integrity of the sampling system is checked regularly by flowing nitrogen through the test apparatus at atmospheric pressure; oxygen concentration is monitored to determine if the sampling system is leak-free. All gases used for calibration of the analyzers were gravimetrically made by Scott Analytical Gases and are traceable to NIST standards. Gas samples can also be analyzed with a gas chromatograph.

The high inlet temperature apparatus has been modified to incorporate steam injection into the combustion air flow. A high precision water flow measuring system has been acquired which is capable of operation at pressures up to 1000 psia and able to measure the low flowrates of water that will be used in this experiment. The water is fed into a steam vaporizer through stainless steel pressurized cylinders equipped with sight tubes so that the flow can be continuously monitored. The electronic flowmeter for the water flow measurement has a precision of 1/4% of full scale, with an operating range of 0.001 to 0.08 GPM. The water flowmeter has been factory calibrated, and this calibration has been checked at UTRC under our proposed operating conditions. The pressurized water cylinders are in place, and all necessary plumbing modifications made to the combustor for steam injection. Several versions of the steam generator and injection system have been built and tested and a design which provides steady steam flow at very low mass flow has been incorporated in the facility.

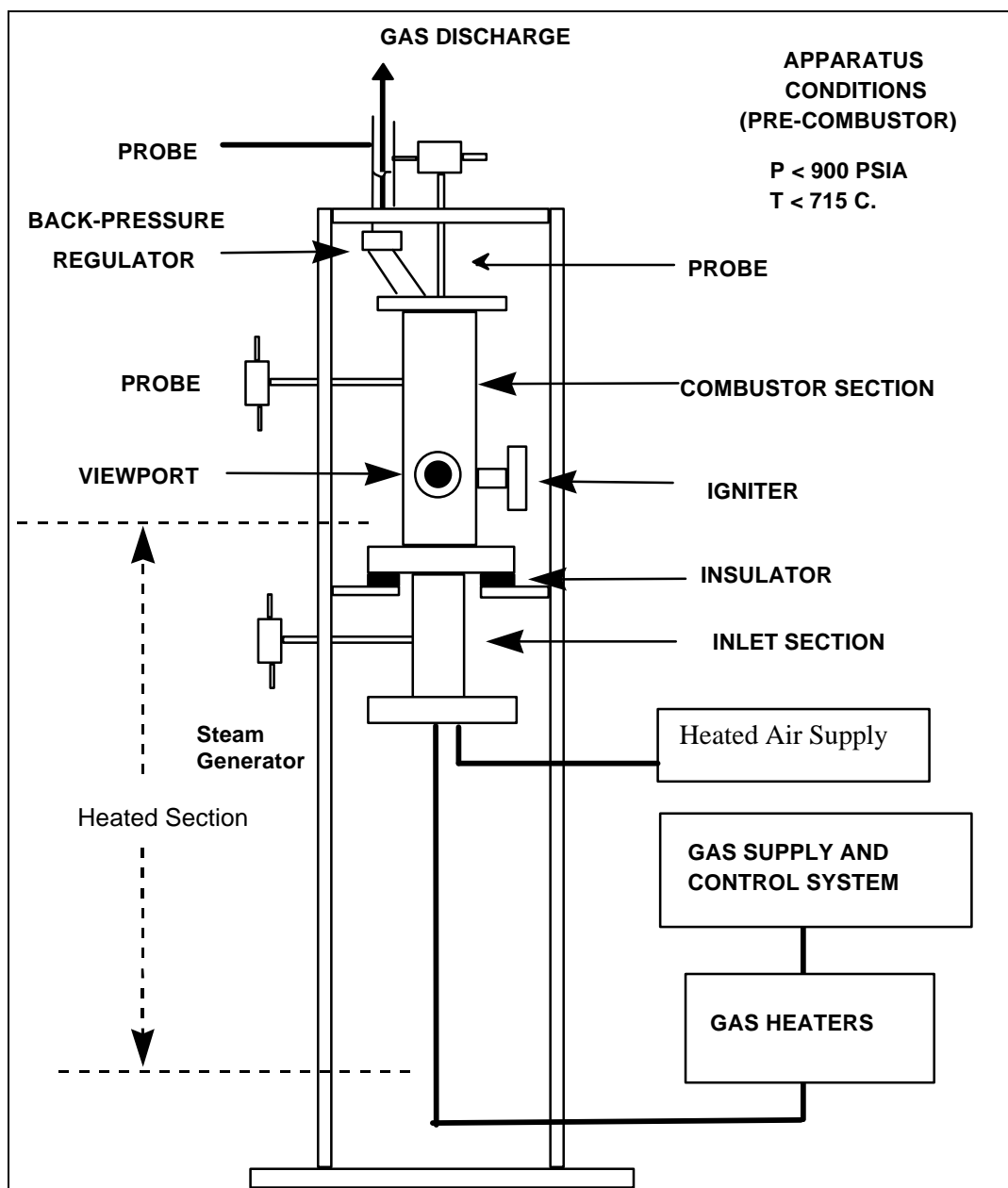


Figure 201-6. Schematic of High Temperature High Pressure Combustion Apparatus

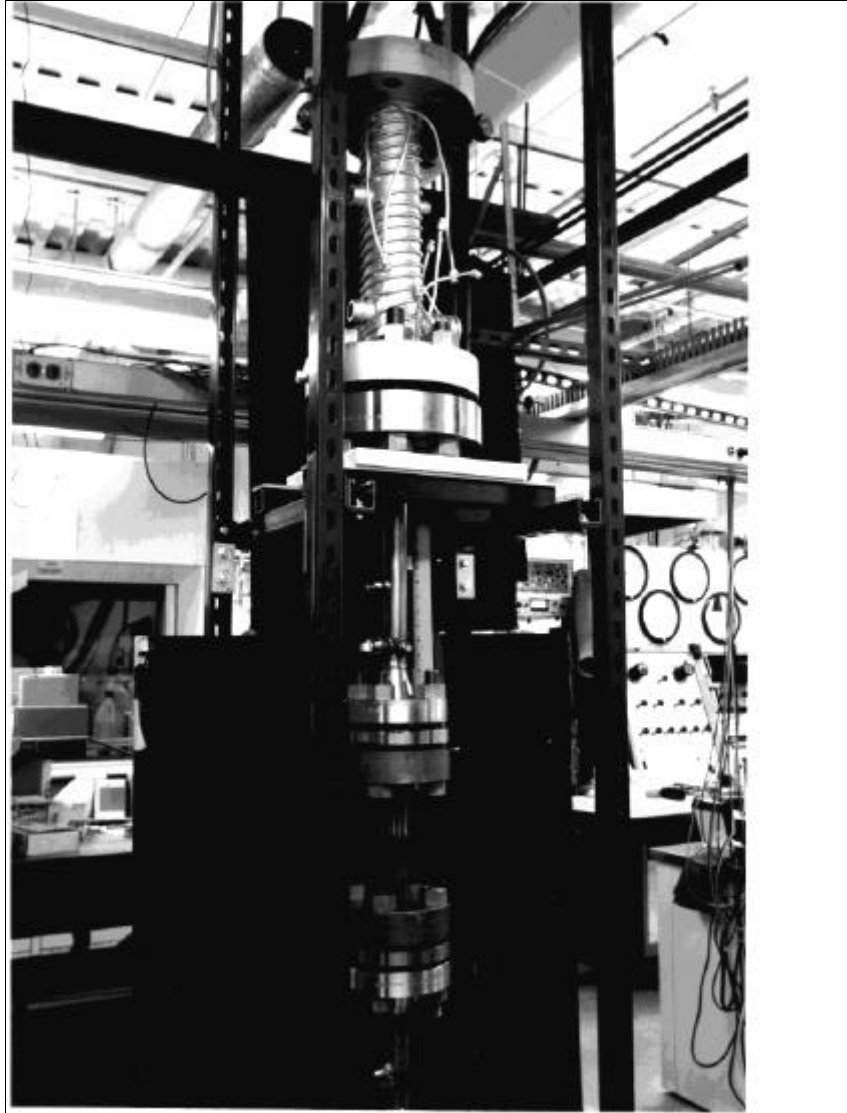


Figure 201-7. Photograph of the High Temperature Combustion Facility

#### NO<sub>x</sub> Measurements in Dry Flames

A suitable, robust burner applicable for investigating the characteristics of premixed flames, specifically with regard to NO<sub>x</sub> generation has been selected based upon prior, UTRC-funded activities. A schematic of this burner, with a representation of a turbulent flame above the burner is provided in Figures 201-8 and 201-9. Such a configuration was selected over the more conventional laminar premixed flames due to difficulties of making such a flame nearly adiabatic (or with controlled/measured heat loss). Such a task is difficult at ambient conditions and is virtually impossible at the elevated inlet pressures and temperatures of interest in this program. In addition, turbulent flames have more practical interest. Hence, the geometry depicted in Figures 201-8 and 201-9 with a turbulent, high mass flow rate flame was selected for study in this program. This burner has several flow paths available for control. In the central tube, the fuel is partially premixed (typically, to

fuel-rich conditions). The mixture exits at the top of a mixing chamber where it flows, along with the remaining 'premixing' air through a narrow annular region. The flow then exits out the top and the mixture burns in a turbulent, premixed flame.

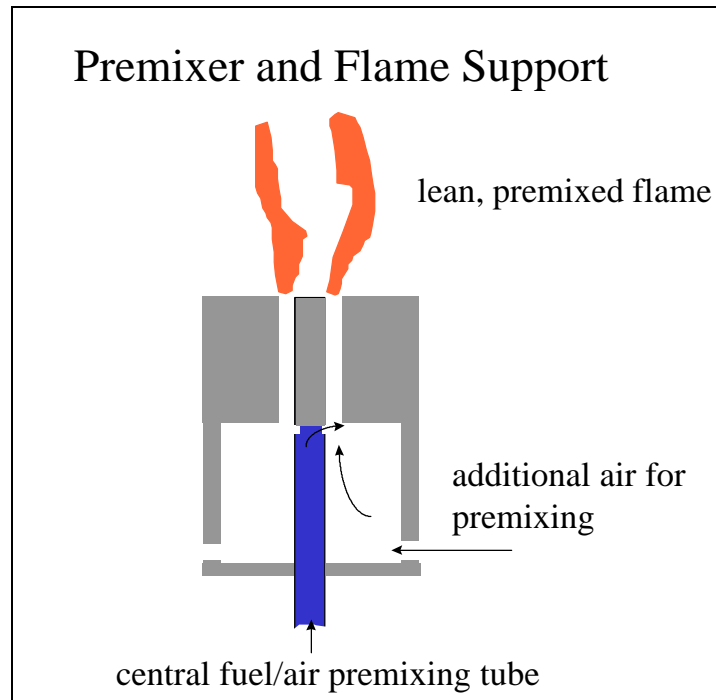


Figure 201-8. Schematic of Partially Premixed Burner System

Initially, we attempted to characterize the performance of the burner under different flow conditions. Tests were performed at 10, 20 and 30 atmospheres and with the air preheated to 700K (800F). In one sequence of tests, at 30 atmospheres and at 725K (845F) preheat, the flame flashed into the premixing chamber and destroyed the burner. This learning experience helped to redefine desired operating conditions for this burner which had been proven to be quite robust for all prior studies at pressures of 20 atmospheres and below. Specifically, minimal flow velocities are desired (not always achievable due to startup transients, etc.) and lower levels of preheat desired. The latter is not perceived to be a problem since applicable ' $T_3$ ' temperatures for the advanced cycles are expected to be in the neighborhood of 590-650K (600-700F) due to intercooling, and flashback should be further inhibited due to the presence of water. To enable higher flow velocities which will also inhibit flashbacks, a new, larger air flow meter for the early premixing core flow was calibrated and installed. Low initial air temperatures may have to be the principal tool for inhibiting flashback under such very high pressure conditions, until yet higher mass flows can be attained.

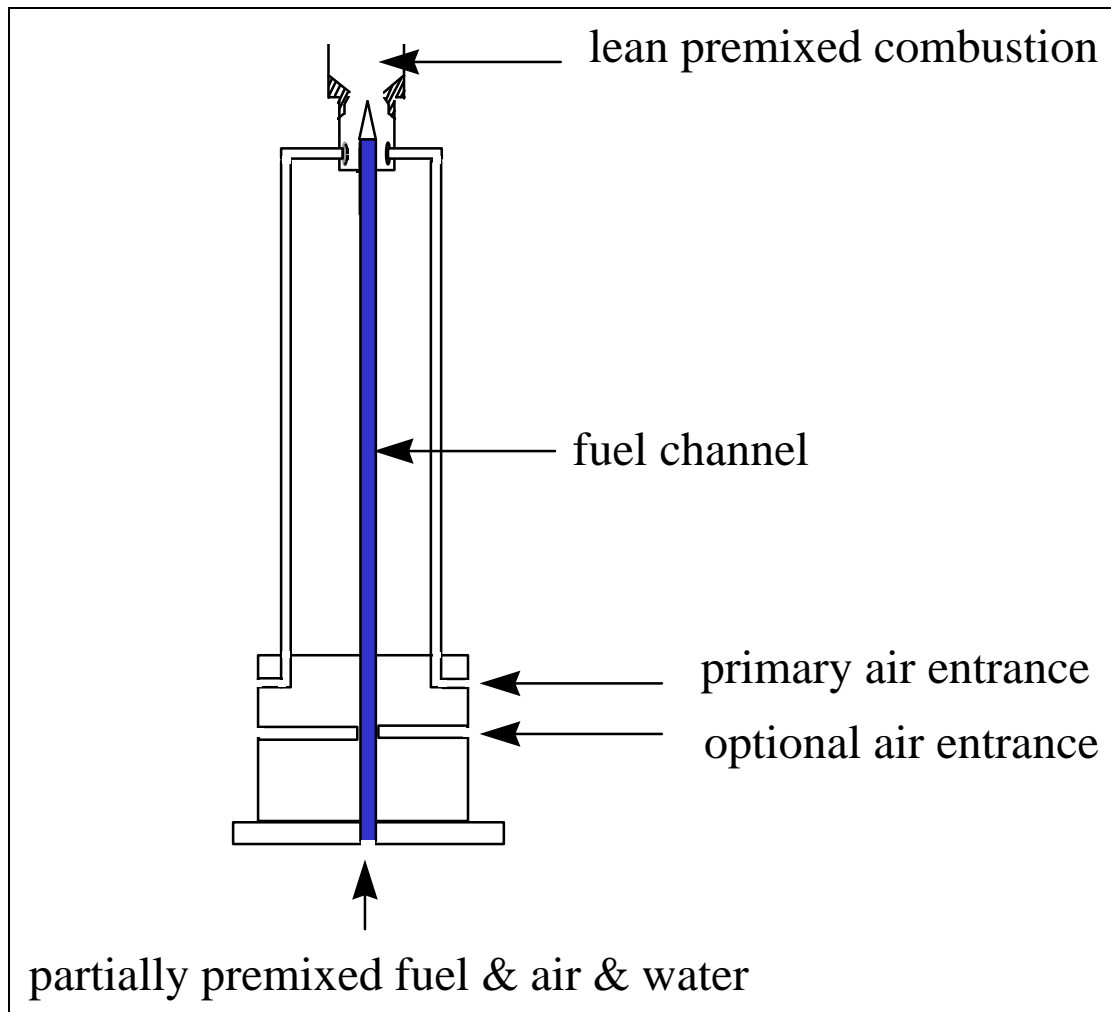


Figure 201-9. Burner Configuration used in High Pressure Combustion Facility

Plots of  $\text{NO}_x$  emissions as a function of the calculated equilibrium flame temperature based on input flow rates for 10, 20 and 30 atmospheres as measured in this burner are shown in Figs. 201-10, 11, & 12. A cursory examination of these data clearly indicates that the scatter is significantly larger than desirable for the intended purposes. Upon careful examination of the data obtained at 10 atmospheres, it was shown that the four lowest  $\text{NO}_x$  levels of the series (B) data set with flame temperatures between 1850 and 1950K (2870 to 3050 F) were obtained with higher flow rates of air in the central premixing tube. These four run points presumably allowed for a greater level of premixing prior to the flame front. The separation of the data in Fig. 201-11 at 20 atmospheres is consistent with this interpretation. Hence, a series of tests were performed in which the flame temperature was held approximately constant while varying the split in the air mass flows between the central tube (for partial premixing  $\text{NO}_x$  emissions for these data are added to the points from Fig. 201-11 and are re-plotted in Fig. 201-13) and the larger premixing chamber.

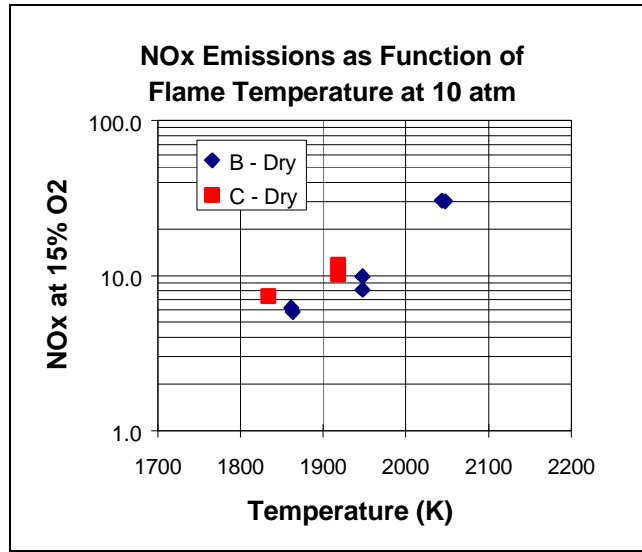


Figure 201-10

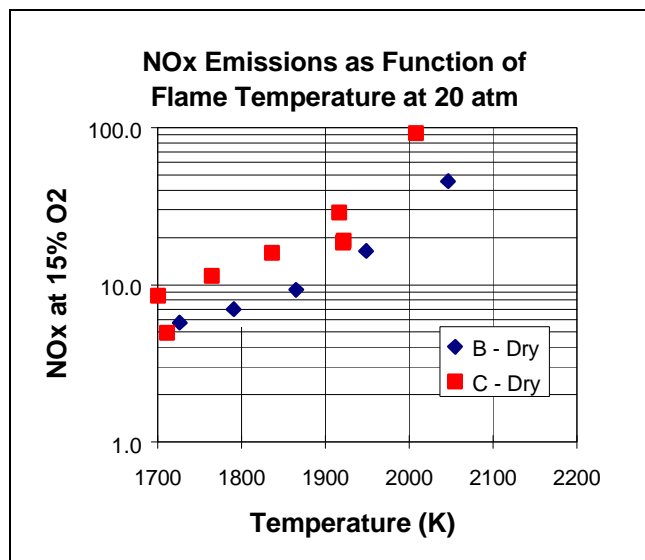


Figure 201-11

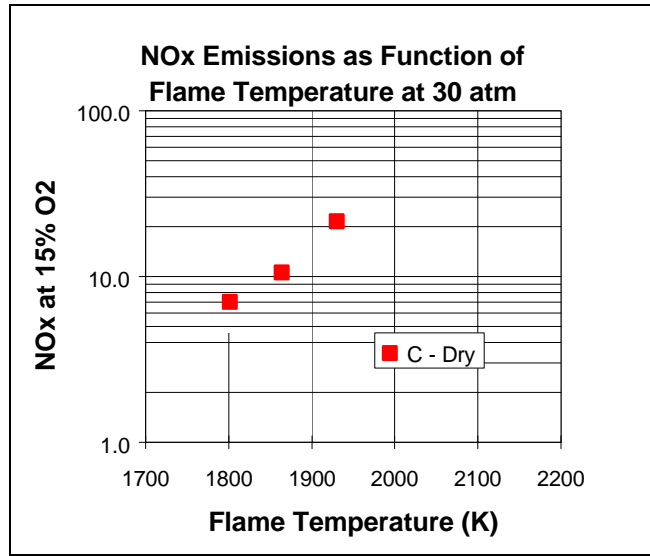


Figure 201-12

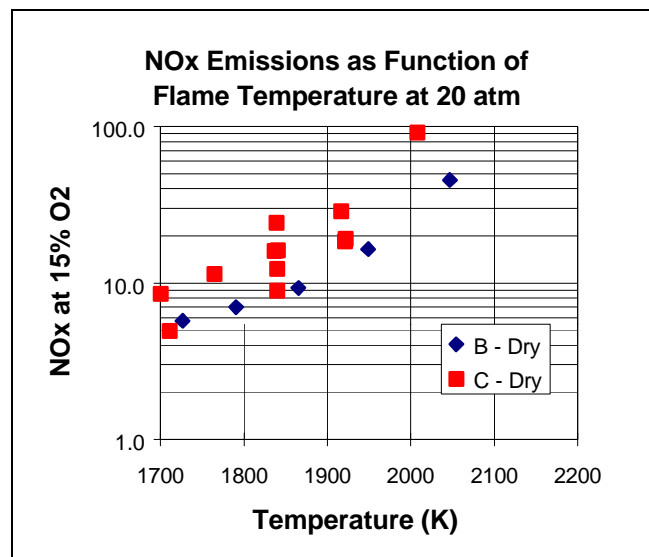


Figure 201-13

The significant variation with changes in the air flow split are quite noticeable. This latter set of NO<sub>x</sub> data at the flame temperature of 1840K (2853F) is also plotted in Fig. 201-14 as a function of the fraction of air flow which is directed through the central tube and used in the partial premixing. NO<sub>x</sub> production should decrease as premixing is increased. Figure 201-14 demonstrates the dramatic decrease in NO<sub>x</sub> with an increasing level of premixing, although the asymptotic value was only approached in this series of runs.

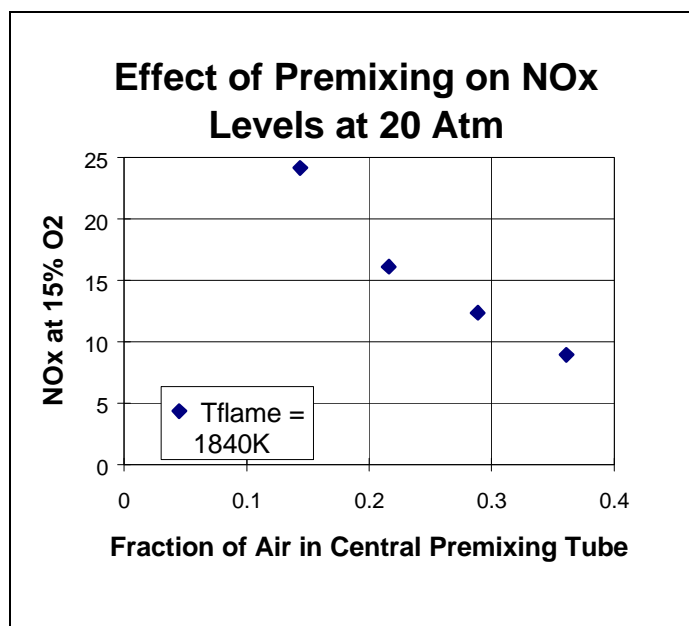


Figure 201-14

This asymptotic value (approximately 5-7 ppm) can be compared to predictions from a perfectly stirred reactor (PSR) and to experimental values reported by Leonard and Stegmaier (1994) for a perfect premixer. In Fig. 201-15, predictions made using GRIMECH2.11 and its associated thermodynamics file are plotted as a function of residence time in a single PSR (CHEMKIN II) as a function of residence time for five different equivalence ratios and, hence, different flame temperatures. The equivalence ratios and equilibrium flame temperatures are reported in the insert. Initial conditions were assumed to be at 20 atmospheres with an air temperature of 725K (845 F) and a fuel temperature (pure methane) of 350K (170 F). The predictions at 0.98, 1.95 and 3.9 msec are also plotted in Fig. 201-16 as a function of equilibrium flame temperature (kinetic calculations indicate that the PSR approaches within 10-15K (18-27 R) of the equilibrium temperature after one millisecond for these conditions and within 3-5K (5-9 R) after 4 milliseconds). Also in Fig. 201-16 is the curve for experimental NO<sub>x</sub> levels from a perfect premixer, as described by Leonard and Stegmaier ("Development of an Aero-derivative Gas Turbine Dry Low Emissions Combustion System," Transactions of the ASME, Vol. 116, p.542, July, 1994). For reference, the approximate asymptotic value of the recent UTRC experiments (shown in Fig. 201-14) of 5-7 ppm is also shown in Fig. 201-16.

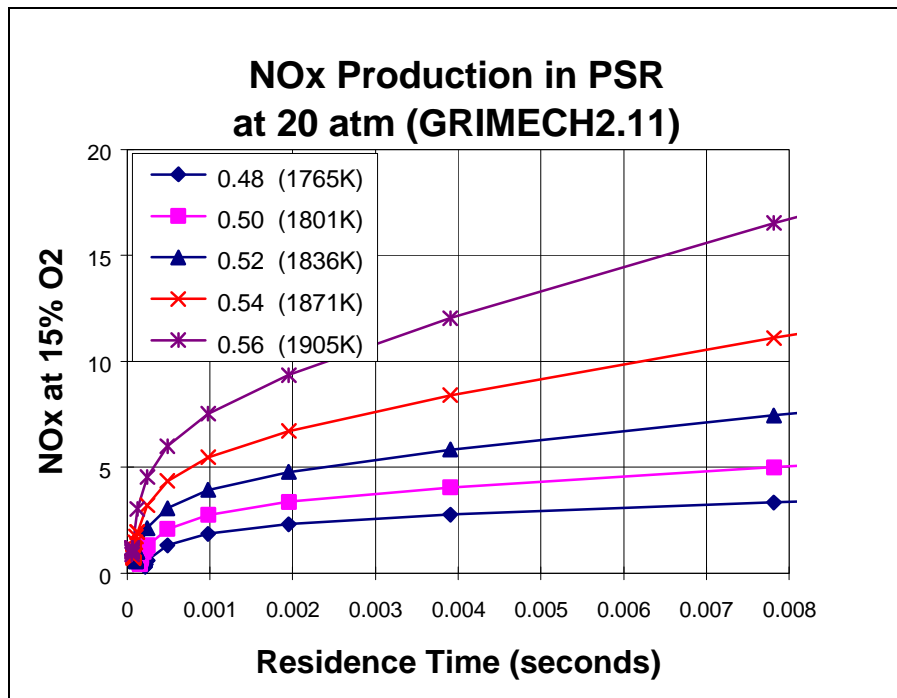


Figure 201-15

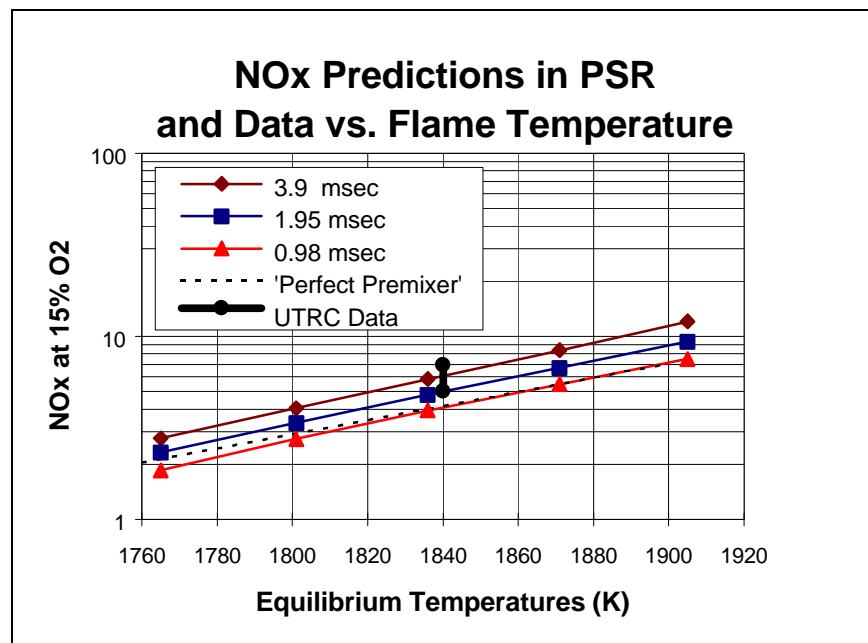


Figure 201-16

The procedure of varying the air flow split to evaluate the effects of unmixedness and to ensure the approach to a near perfect level of premixedness can be followed to attain related data over a range of pressure and temperature conditions. This data can be used for comparison to the previous (literature) data as well as to validate GRIMECH2.11

under gas turbine conditions. Furthermore, the same or slightly modified procedure can be used for the case of steam addition to the air. Such experiments along with modeling validation will be a main focus of the remainder of this task.

#### Solubility of air in water at elevated pressures.

In our laboratory studies of combustion under simulated HAT-cycle conditions, water is pressurized up to 60 atm with air. Finite solubility's of air in water at these pressures raises fear that air carried in the vaporized water stream may effect the equivalence ratio during combustion. A calculation was hence performed in order to determine the mole fraction of air that can be present in water. This calculation can be performed in two different ways: a rough calculation assuming ideal solubility (gives solubility within an order of magnitude) and a more accurate and reliable calculation based on experimental data (with some engineering approximations). The ideal solubility calculation is

independent of the solution and is proportional to pressure,  $x = \frac{y_2 P}{P_{vp2}}$ , where  $y_2$  is the mole fraction of the component in the vapor phase,  $P$  is the system pressure and  $P_{vp2}$  is the vapor pressure of the solute. This calculation gives higher solubilities than seen experimentally (a mole fraction of  $10^{-3}$  for  $N_2$  in  $H_2O$  at  $25^\circ C$  and 1 bar pressure)

In a more practical approach Krichevskiy-Kasarnovsky equation (The Properties of Gases and Liquids by Reid, Prausnitz, and Poling, 1986) was used to predict the solubility of nitrogen in water at elevated pressures:

$$\ln\left(\frac{f}{x}\right)_2 = \ln\left(\frac{y_2 P}{x}\right)_2 = \ln H_2 + \frac{V_2^\infty P}{RT}$$

where  $f$  is the fugacity of the gas,  $\phi$  is the fugacity coefficient of the gas,  $x$  is the mole fraction of the gas in solution,  $H_2$  is the Henry's constant,  $P$  is the system pressure, and  $V_2^\infty$  is the partial molar volume of the gas at infinite dilution in the liquid phase. This equation predicts the experimental solubilities remarkably well up to about 650 bars.

The assumptions made in this approach are that the composition of air is assumed to be 100% nitrogen (oxygen and nitrogen have very similar solubilities in water, with oxygen being slightly higher), and that the fugacity coefficient  $\phi$ , follows the Lewis rule and remains constant in the 1-100 bar pressure range (the precise value of  $\phi$  can be calculated from different equations of state). The experimental value of solubility at 1 bar and  $25^\circ C$  (the approximate storage temperature in our high pressure vessels) was used to calculate the value of  $\phi$ . The value for Henry's constant and  $V_2^\infty$  were evaluated from experimental data (Molecular Thermodynamics of Fluid-Phase Equilibria by Prausnitz, Lichtenthaler, and Azevedo, 1982). The results from this calculation are shown in Figure 201-17.

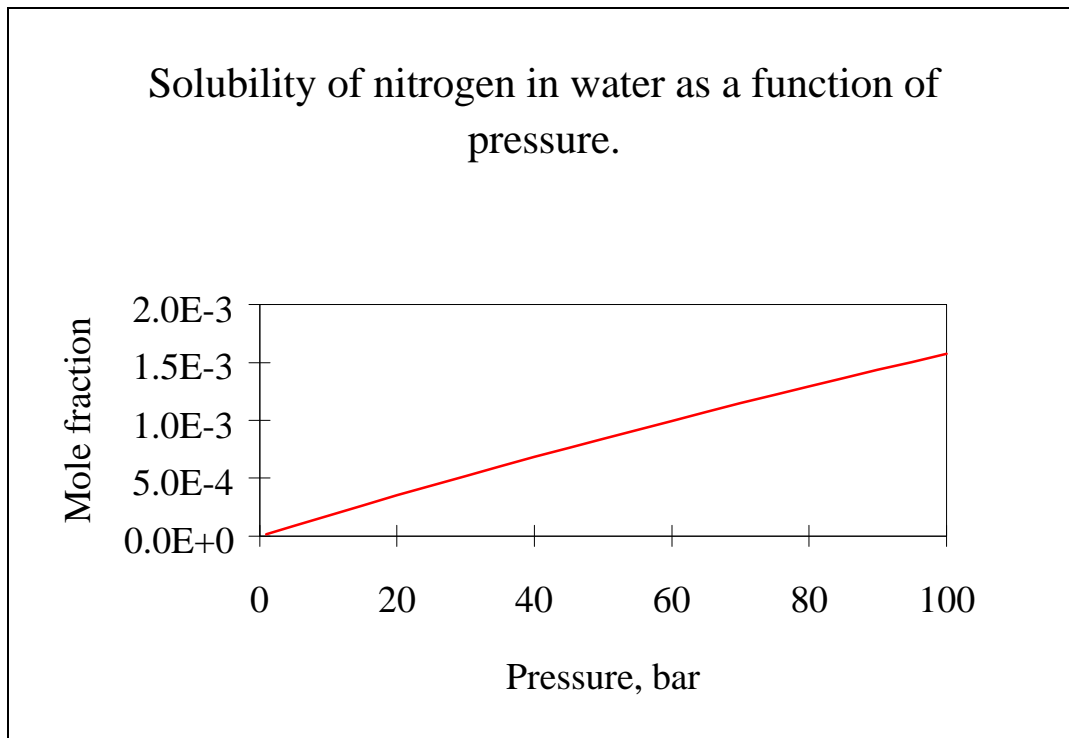


Figure 201-17. Solubility of Nitrogen in Water at High Pressure

This curve indicates that water pressurized by air up to 60 atmospheres would attain only 0.001 mole fraction of nitrogen. A similar result could be obtained for oxygen. Since the mole fraction of water vapor in air in a HAT cycle can be expected to be 0.2 to 0.3, the added air from the water vapor amounts to only about 0.0003 mole fraction in the mixture. Hence, these calculations demonstrate that the dissolved air carried with the water can be neglected.

### Chemical Kinetic Modeling

As an example of the type of calculations which have been performed, compare the combustion of three fuels, all at 20 atmospheres and at inlet air, fuel (natural gas) and steam temperatures of 700K (800 F). The first fuel is natural gas, assumed to be at 700K. The second is a mixture of fuel and steam at 700K (800 F). with an effective steam/air mass ratio of 0.0915. The third fuel is a 'reformed' fuel mixture of methane, steam, and air (mass fractions of 0.233, 0.612, and 0.155 , respectively) initially at 700K (800 F), but once reacted attains the temperature of 762K (912 F). This fuel 'processing' is comparable to the autothermal reaction system proposed for gas turbine systems. The mass fraction of water in the total air stream for this autothermal case is the same as in case 2. All three are fueled at a rate to produce an (equilibrium) flame temperature of 1811K (2800 F). A series of calculations were performed for each mixture using a modified perfectly stirred reactor (PSR) code (Ref. 3) and the 'GRI-Mech version 2.11' chemical kinetic reaction set. In each case, the residence time in the PSR was reduced sequentially until the mixture could no longer support combustion. This limiting residence time has been shown to provide a

measure of overall flame stability (Ref. 4). As the PSR residence time, or tau, is reduced the reaction chemistry is no longer fast enough to provide heat release sufficient to sustain combustion and reaction temperatures are suppressed. In Fig. 201-18, are plotted the PSR temperatures for each of the three fuels as a function of PSR residence time.

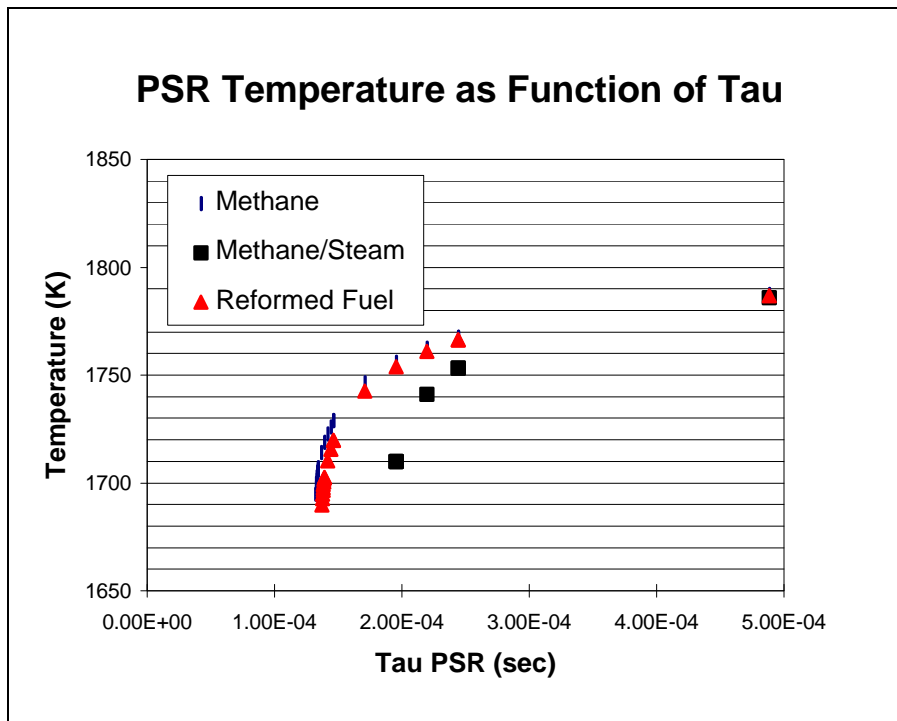


Figure 201-18

As can be seen, the methane/steam system suffers from a greater level of instability relative to the other flames and suggests that any combustion device must require a greater volume or otherwise enhanced stabilization features to ensure a robust combustion system. Figure 201-18 also shows the fact that with the same incoming enthalpy, steam and methane, air flows, an autothermal reactor can ‘reform’ the fuel into a more reactive condition such that minimal penalty is sustained in combustion stability despite the substantial addition of steam to the system. Further advantages of the steam addition and particularly the autothermal approach can be found by examining the predicted emissions (corrected CO and NO<sub>x</sub>) in Figures 201-19 and 201-20 for these same conditions.

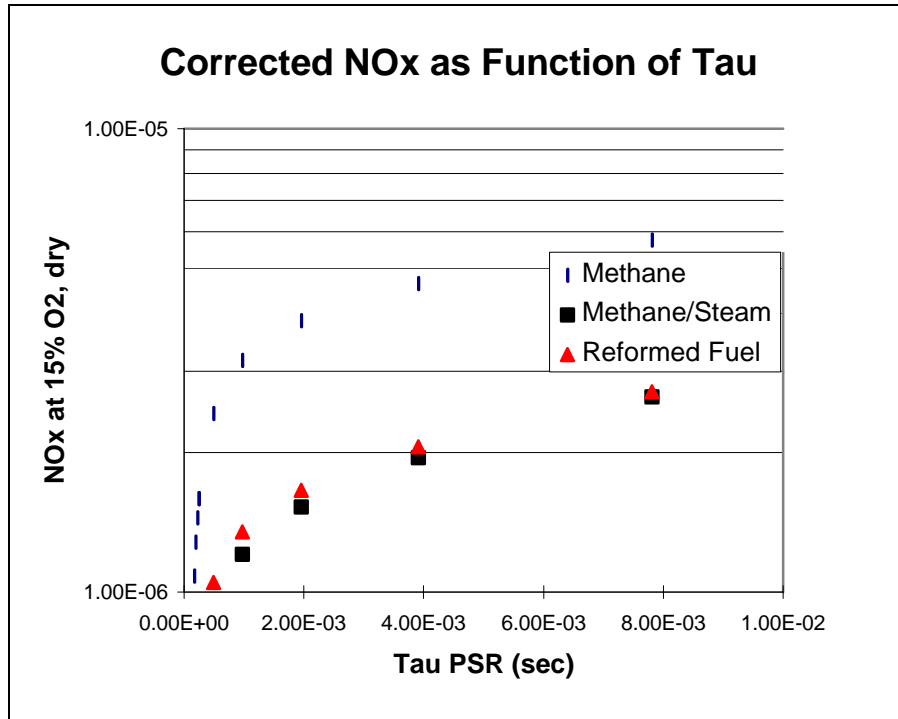


Figure 201-19

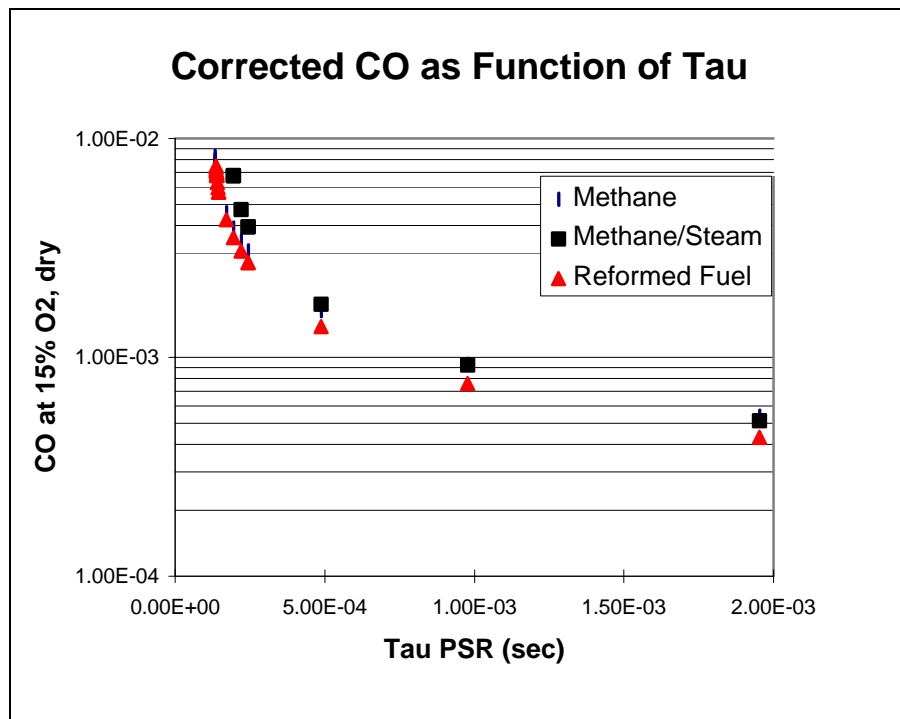


Figure 201-20

Figure 201-19 shows how steam (unreacted or reacted with the fuel) can lead to a substantial decrease in NO<sub>x</sub> production rates. An analysis indicates the reduction in NO<sub>x</sub>

production due to the presence of high concentrations of water is due to the dilution effect of the steam and to the suppression of the O-atom concentration, a key intermediate in the production of flame-generated  $\text{NO}_x$ . As can be seen in Fig. 201-20, CO benefits are also possible with the use of the 'reformed' fuel. It will be an objective of the combined experimental and modeling efforts to verify the validity of predictions such as these.

These chemical kinetic tools will be used also to develop reduced reaction sets for use in CFD codes. Computational fluid dynamic models such as FLUENT® which is licensed for use at UTRC or CORSAIR can only accept limited reaction sets (for example, less than 10 species). The complex flow field that will be present in a proposed burner design can be examined analytically using such codes to examine residence times, flow velocities, areas of recirculation, regions of incomplete CO oxidation and general flow characteristics which may aid in screening burner concepts prior to testing in the small scale combustor. The modeling effort will be used to predict the performance of burner configurations in the full-scale combustor.

#### Schedule and Planned Activities

Figure 201-21 below illustrates the present program plan and schedule for Task 201. Upon examination of this previously presented schedule, activities under this task are on target with respect to the overall program timeline. In the near future, testing will be performed in the high pressure combustor with water addition. A focus area in the fundamental data base generation task will be varying the air flow split to evaluate the effects of unmixedness and to ensure the approach to a near perfect level of premixedness. This data can be used for comparison to the previous (literature) data as well as to validate GRIMECH2.11 under gas turbine conditions. Furthermore, the same or slightly modified procedure can be used for the case of steam addition to the air. Development of a more fully premixed burner which will operate robustly at high pressure will proceed based upon the results of the effects of premixing as presented in Figure 201-14 above.

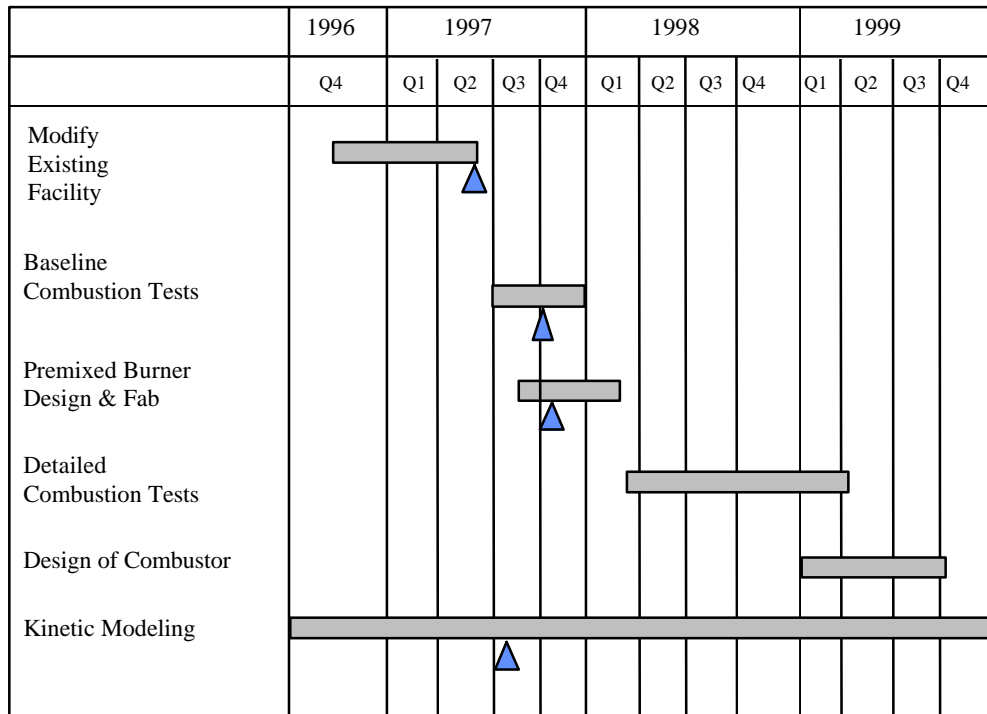


Figure 201-21. Task 201 Program Plan Schedule

## Task 203: FETC Combustion Evaluation Studies

### Objectives

The objectives of this task are to assess experimentally the effect of high moisture levels in the air stream on emissions, stability limits, operational trades, ignition and humidity ramp-up at conditions representative of a Humid Air Turbine (HAT) gas turbine system. The experimental assessment is to be conducted at the FETC facilities in Morgantown, West Virginia. The importance of fuel nozzle and liner design parameters will be investigated under Humid Air operating conditions. In addition, the effect that fuel composition has on the combustion process when combined with humid air conditions will be investigated.

The test program will be segregated into three phases. Under the first phase, fuel injector designs will be investigated. Emissions performance, dynamic characteristics, and injector durability will be evaluated. The second phase will be the examination of flame stability enhancements and liner designs. Performance evaluations will be based on emissions, dynamic response characteristics, and liner heat transfer characteristics. Finally, phase three will focus on the effect of natural gas composition(s) and simulated low / medium Btu fuels on combustion system performance.

### **Phase 1: Injector Design Evaluation**

#### **Objectives**

The test facilities at FETC have a limited maximum flow capacity of 2.2 lb/sec of dry air. However, the facility does offer the opportunity to test up to 400 psia. To take advantage of the pressure capability, a test program has been developed to examine different scale nozzles to allow comparison to existing data bases as well as extend the data base to higher pressure operation. Specific objectives include:

- Demonstrate and verify aerothermal design methodology to scale existing fuel injector hardware to size consistent with FETC facility capabilities
- Evaluate emissions performance under dry air operating conditions
- Measure dynamic pressure response of the combustion system
- Evaluate combustion performance under humid air conditions
- Evaluate alternative fuel nozzle designs

### **Test Matrices @ FETC Facilities**

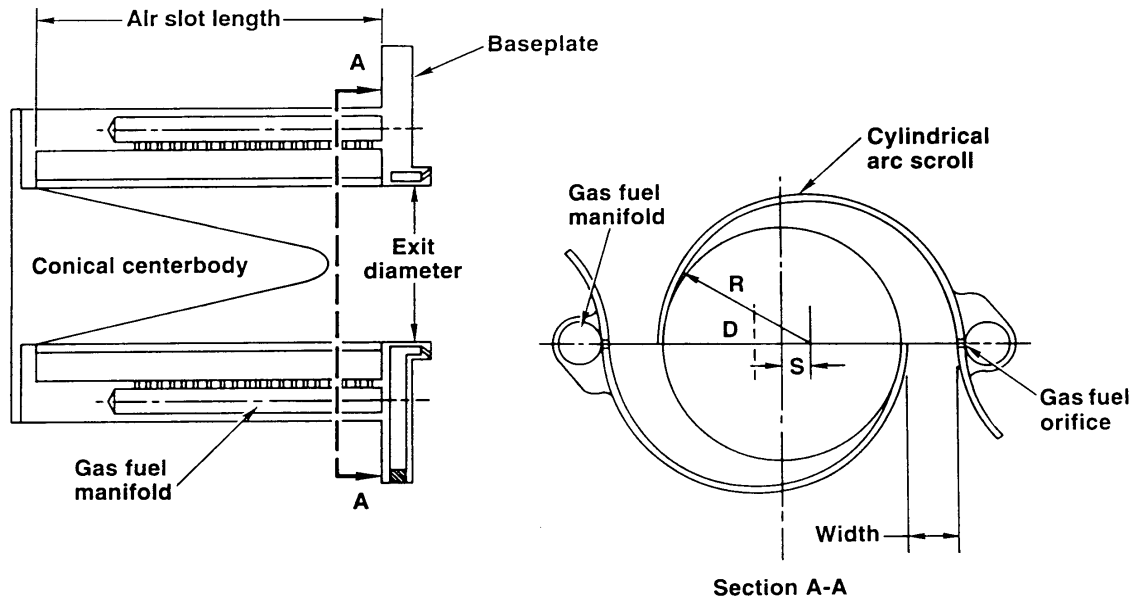
Parametric variations will include:

- Influence of equivalence ratio on emissions performance
- Effect of inlet pressure and temperature
- Effect of combustion section reference velocity (nozzle pressure drop)
- Influence of humid air concentration

- Influence of piloting on injector stability and emissions

The initial test program at FETC will focus on a derivative of the Tangential Entry fuel nozzle design (see Figure 1) that has been studied at the United Technologies Research Center.

Figure 1  
The Tangential Entry Nozzle



Some of the parameter ranges that will be investigated include:

Pressure: up to 400 psia

Inlet Air Temperature: upto 860 °F

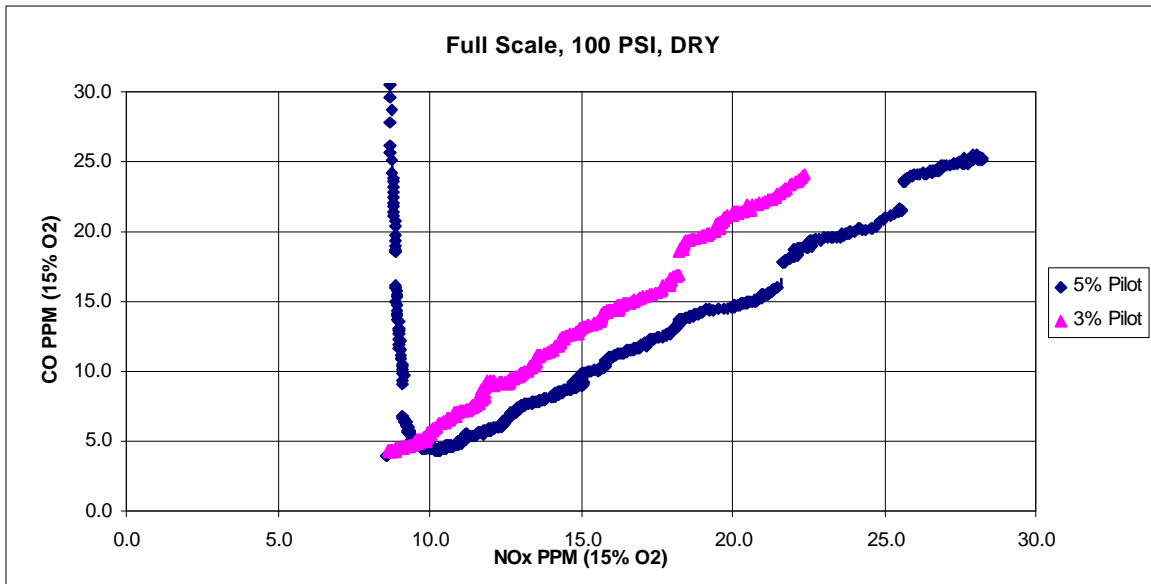
Water(%) by mass in the air: up to 20 %

Flame Equivalence Ratio: 0.48 - 0.96

In these tests, the assessment of the effects of fuel split, moisture level in the air, inlet air temperature, combustion pressure and hardware scale will be made. A constant range of flame temperatures will be used as moisture level is varied. The results of this test program will feed into HAT cycle modeling activities to determine target cycle performance characteristics for a HAT engine. The cycle analyses that follow the initial test program will guide test matrix development for all subsequent test programs.

Initial shakedown testing of the nozzle has been completed in the FETC facility at 100 psi pressure using dry air. The measured NO<sub>x</sub>-CO relationship is shown in Figure 2 for two different levels of diffusion pilot. The steam that will be used for humidifying the air was not available during the shakedown testing that generated these results.

Figure 2  
NO<sub>x</sub>-CO Relationship During FETC Facility Shakedown Testing

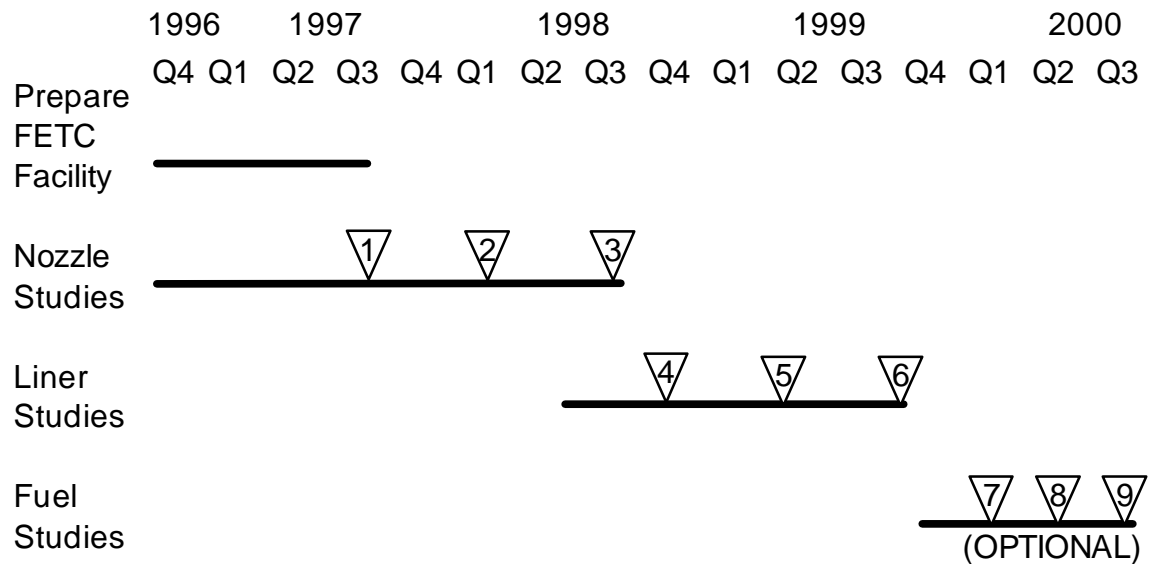


The second and third test programs in this phase at FETC will be similar in scope to the initial test program. Items such as the effect of reference velocity and the effect of piloting which is not part of the initial test program will be considered in the second and third test programs along with the investigation of alternative nozzle and piloting designs.

## Schedules

The test program target dates for testing at the FETC facility are shown in Figure 3.

FIGURE 3  
PLANNED FETC TEST ACTIVITY



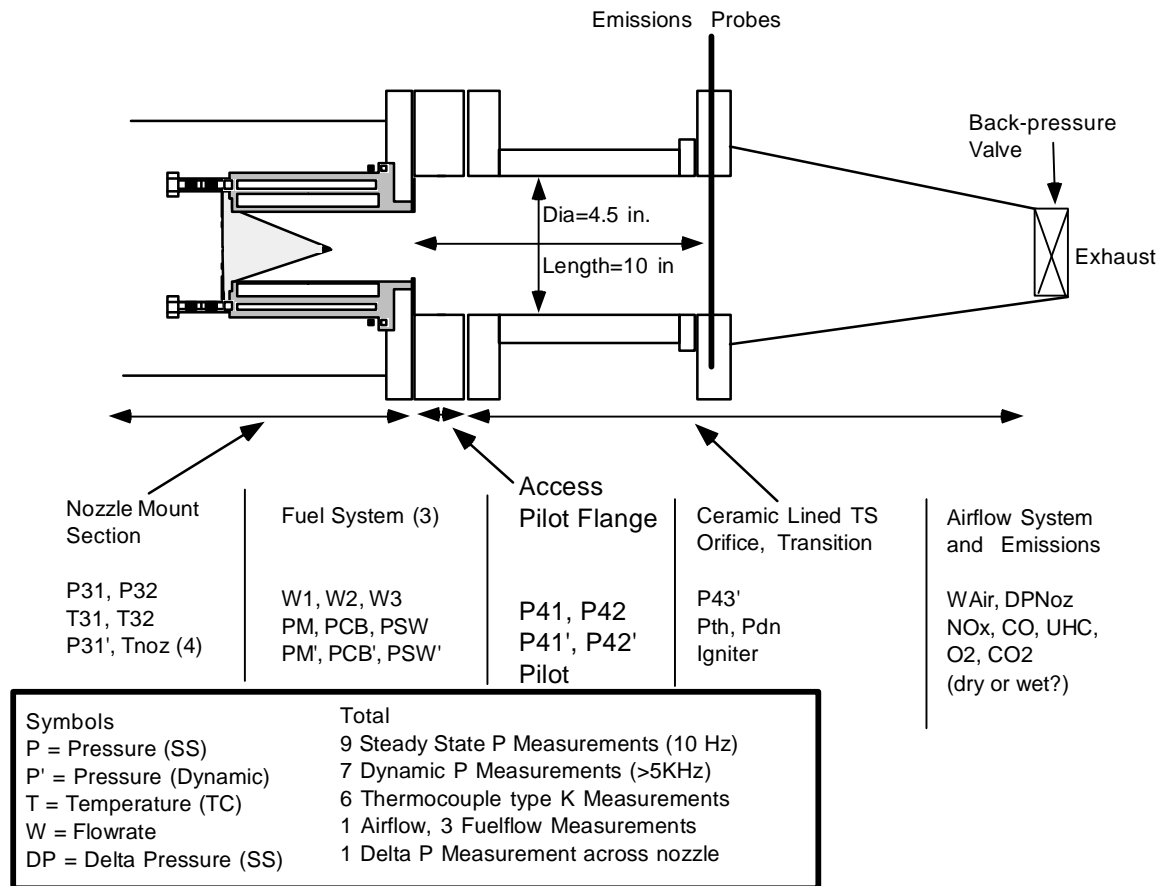
▽ = TESTING AT FETC FACILITY

**Note :** Tests 7, 8, 9 denote the Optional Low BTU Gas Studies

Figure 4 shows the instrumentation specified for the initial test program at FETC. The combustor will be a cast ceramic. The rig instrumentation will include pressure transducers, dynamic pressure transducers, a differential pressure measurement across the nozzle, thermocouples, and flow monitoring devices.

**Figure 4**

## Instrumentation & Rig Requirements for Fetc Facility



## Phase 2: Liner Design & Flame Stability

### Objectives

- Evaluate lean stability enhancement techniques
- Evaluate combustion system response (emissions, stability, dynamics) to a convectively cooled liner .
- Evaluate non traditional combustor design concepts, such as series staged configurations.
- Evaluate combustion system response to a liner geometry incorporating passive acoustic control features.

## **Approach**

An analytical CFD model of the combustion system including the dynamic response is being constructed. Dynamic pressure measurements taken with a conventional film cooled liner will be used to calibrate and verify model predictive capabilities. Phase two test data taken with a convectively cooled liner will be used to determine the change in combustion system dynamic response and overall emissions performance. Test matrices will be similar to the Phase 1 testing. The schedule is as shown in Figure 3.

## **Phase 3: Fuel Composition Effects**

### **Objectives:**

- Evaluate the influence of varying natural gas composition on combustion system performance
- Evaluate the effects of a low / medium BTU fuel on fuel injector robustness and combustion system performance

## **Approach**

Test matrices will be similar to the Phase 1 testing. A single fuel nozzle and liner concept will be used throughout the fuel evaluation study. The schedule is as shown in Figure 3.

## **Acknowledgements**

The Contracting Officer's Representative on this program is Lee Paulson. Contributors to Task 201, in addition to Brian Knight, were Anuj Bhargava and Med Colket of the United Technologies Research Center. The work of Task 203 was done by William Sowa of UTRC. The period of performance for the work covered in this report is October, 1996 to September, 1997.

## References

1. J.J. Sangiovanni, M. B. Colket, W. R. Davison, R. P. C. Lehrach, E. Welch, B. A. Knight, and T. R. Snider, "Hybrid Combustion for Ultra-Low NO<sub>x</sub> Emissions," Final Report to Gas Research Institute, GRI-95/0291, November, 1994.
2. R. J. Kee, F. M. Rupley, and J. A. Miller, "CHEMKIN-II: A Fortran Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics," Sandia National Laboratories, SAND89-8009, UC-401, March, 1991.
3. P. Glarborg, R. J. Kee, J. F. Grcar, and J. A. Miller, "PSR: A Fortran Program for Modeling Well-Stirred Reactors," Sandia National Laboratories, SAND86-8209, February, 1986.
4. S. Hoffman, P. Habisreuther and B. Lenze, "Development and Assessment of Correlations for Predicting Stability Limits of Swirling Flames," Chemical and Engineering Processing, 33, pp. 393-400, 1992.

# DOE-FETC HAT Cycle Technology Development Program

## Task 203: FETC Combustion Evaluation Studies

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William Sowa

October 28, 1997

# Task 203 Objectives

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- Identify the effect of moisture content in the air stream on emissions, stability limits, operational trades, ignition and humidity ramp-up
- Evaluate the importance of nozzle design parameters, liner design parameters and fuel type operating at HAT conditions
- Evaluate the effect of nozzle scale on performance

# Approach

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- Fuel Nozzle Screening
  - Conduct tests at FETC facility by adding steam to dry air to simulate HAT conditions
  - Vary fuel nozzle scale to operate at a range of pressure conditions (up to 400 psi)
  - Examine different nozzle designs leading to the selection of a preferred design
  - Map stability margins, NO<sub>x</sub>, CO, efficiency and pressure dynamics

# Approach

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- Liner Screening
  - Conduct tests at FETC facility at simulated HAT conditions
  - Examine different liner concepts from ceramic adiabatic walls to convectively cooled designs
  - Utilize a single fuel nozzle
  - Characterize stability boundaries, emissions and pressure dynamics at simulated part power operating conditions

# Approach

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- Fuel Type Studies (Optional)
  - Conduct tests at FETC facility at simulated HAT conditions
  - Utilize a single fuel nozzle and liner concept
  - Vary fuel type examining high and medium BTU gaseous fuels
  - Map stability boundaries and emissions as fuel/air ratio,  $H_2O$  loading, pressure and air temperature vary

## Current Year Tasks

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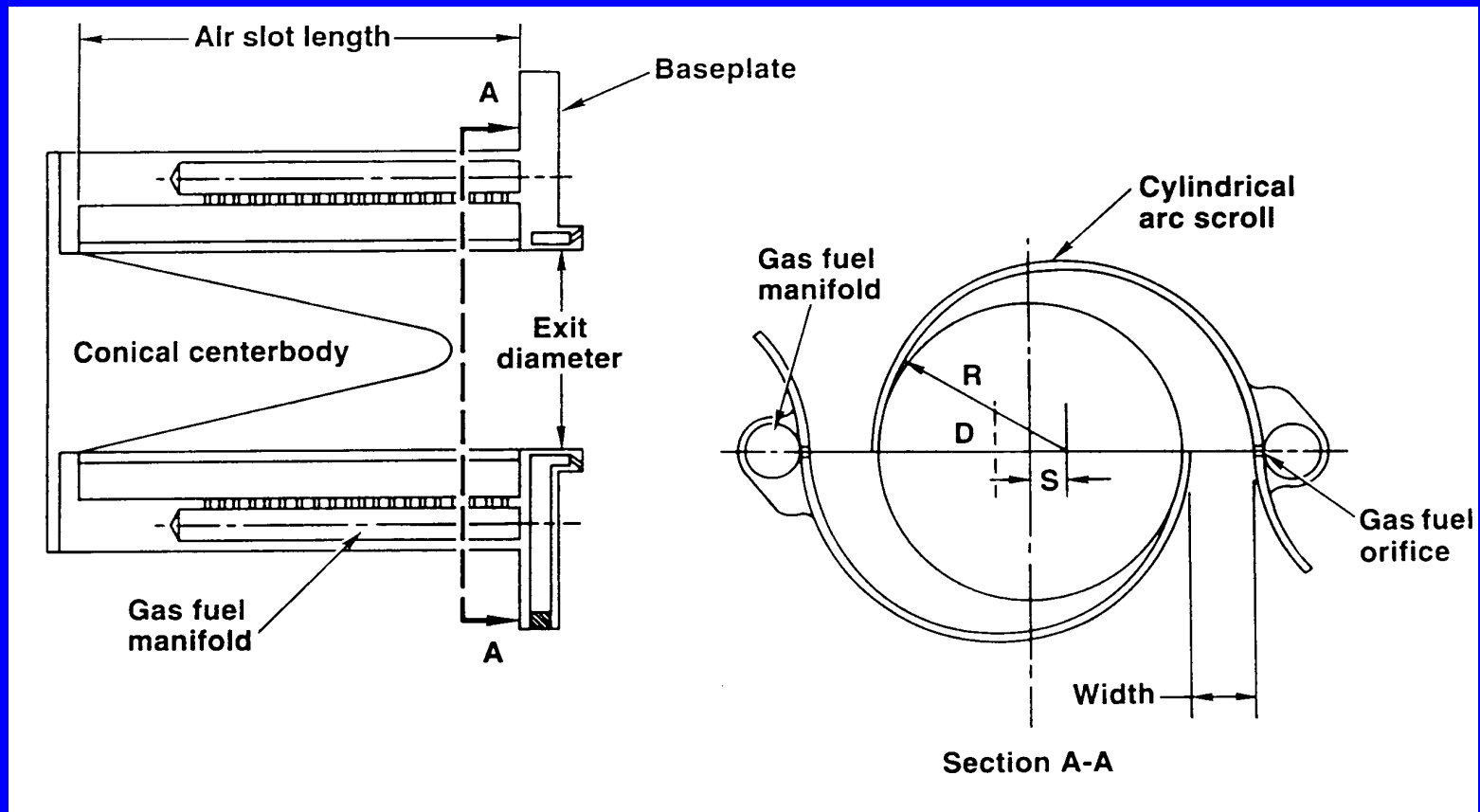
- Design and fabricate fuel nozzles for test at FETC facility
- Baseline the performance at the FETC facility against existing UTC data bases
- Conduct detailed experiments to determine effects of T, P, [H<sub>2</sub>O] and fuel nozzle scale on emissions
- Use results as input to the next design iteration and analysis activities

## Progress to Date

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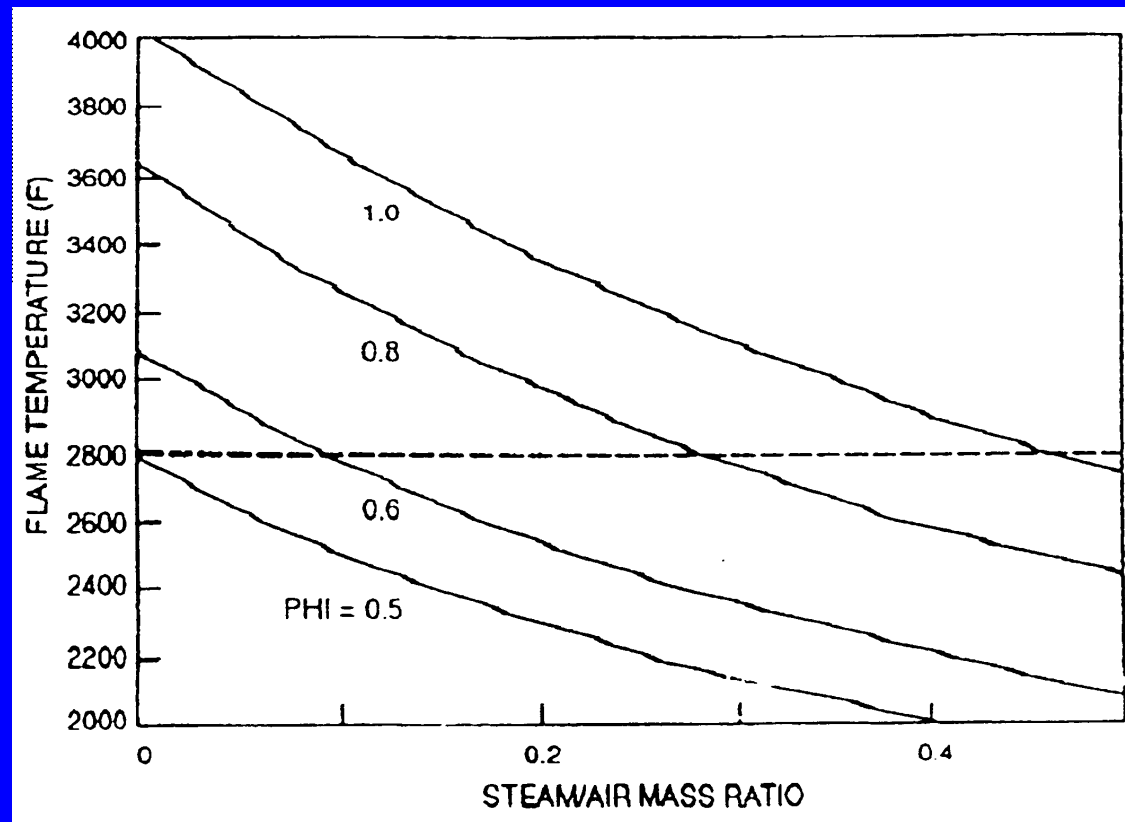
- 3 nozzles have been fabricated varying in scale and delivered to FETC for testing
- Initial shakedown testing has shown reliable light-off and operational characteristics of the largest nozzle
- FETC facility is preparing steam lines for HAT condition simulation

# First Nozzle Concept Tested is from the Tangential Entry Nozzle Family



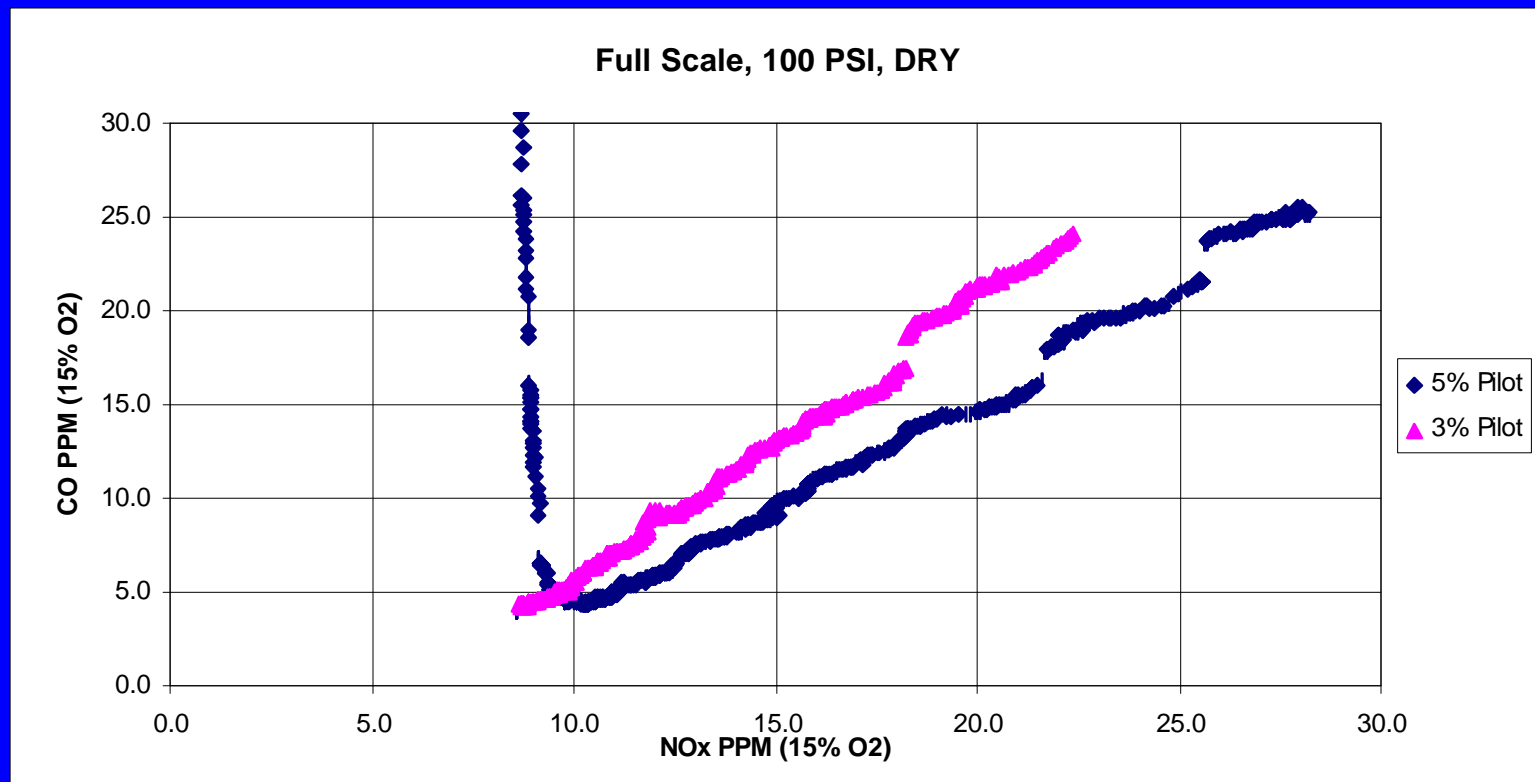
# Stability Margins are Expected to Follow Flame Temperature Trends

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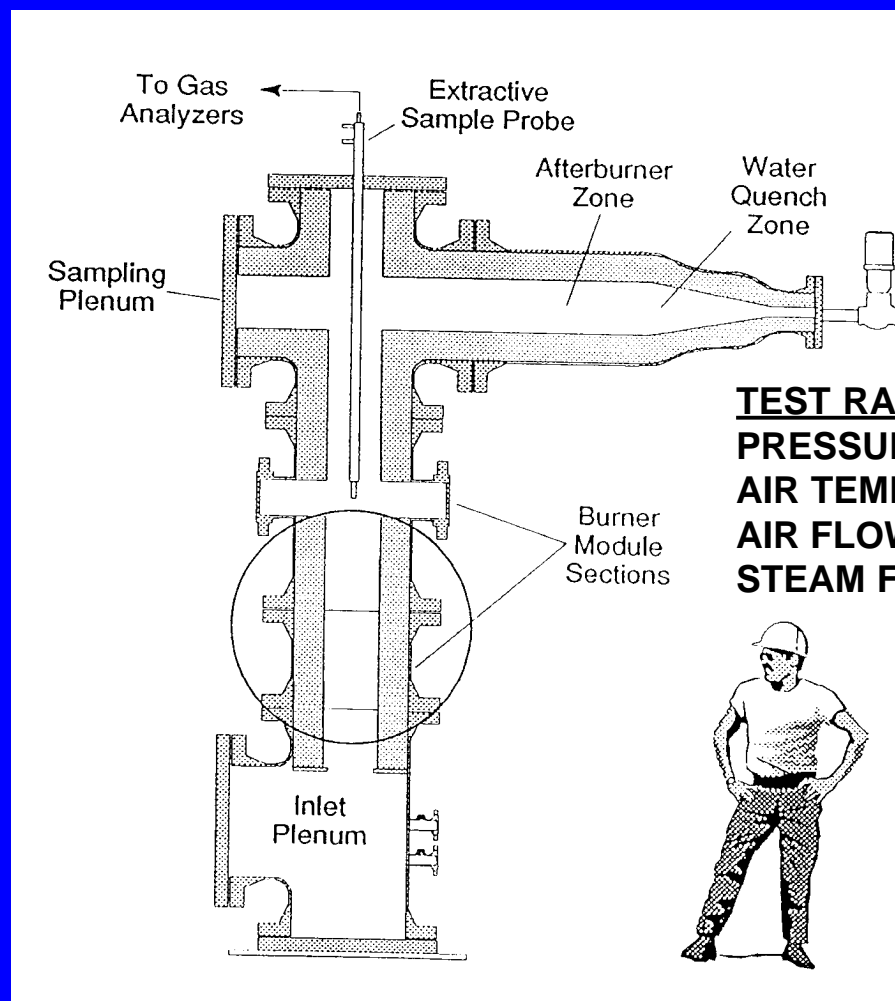


# NO<sub>x</sub>/CO Relationship for Two Piloting Levels

## (Shakedown Test Results)



# Schematic of FETC High Pressure Burner Facility

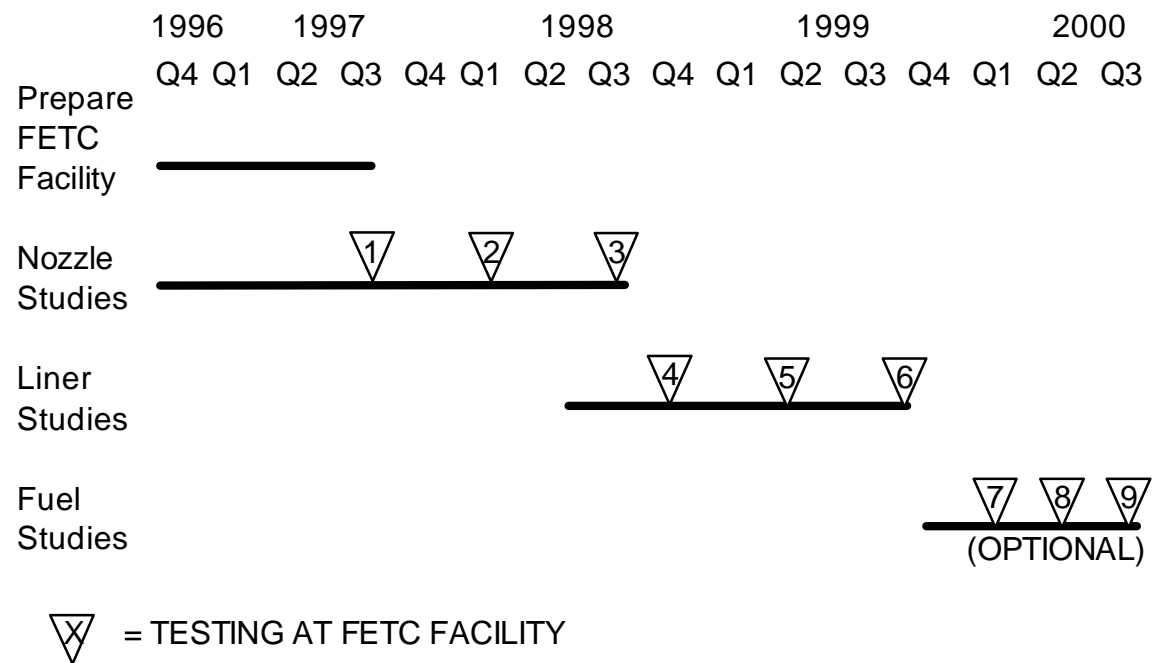


## TEST RANGE

**PRESSURE:** UP TO 400 PSIA  
**AIR TEMPERATURE:** UP TO 1000°F  
**AIR FLOW RATE:** UP TO 2.2 LB/SEC  
**STEAM FLOW RATE:** UP TO 0.45 LB/SEC



# Task 203 Program Schedule



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# HAT Cycle Technology Development Program

William H. Day

Manager-Advanced Industrial  
Programs, Pratt & Whitney

October 29, 1997

# DOE-FETC HAT Cycle Technology Development Program

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## Task 201: Kinetic Modeling and Fundamental Database Generation

Anuj Bhargava

Med Colket

Brian Knight

October 28, 1997

# Task 201 Objectives

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- u Evaluate the stability limits and emissions from natural gas flames with H<sub>2</sub>O addition at temperatures and pressures representative of the HAT cycle
- u Utilize the results of small scale combustion experiments and kinetic modeling to guide in the design of a full scale fuel nozzle and combustor system

# How Will UTRC Meet The Task 201 Program Objectives?

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- u Fundamental Data Base Generation
  - Conduct tests of premixed and/or diffusion flame burners to evaluate the effect of water addition on emissions and flame stability as a function of temperature and pressure
- u Chemical Kinetic Modeling
  - Modify kinetics codes to account for humid air and pressure dependence on species production

# Task 201 Focus Areas

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- u  $\text{NO}_x$ , CO, UHC production as a function of pressure and moisture content of air
- u Resolve premix vs diffusion flame  $\text{NO}_x$  and CO production issues under HAT cycle conditions
- u Development of modeling tools to account for effects of moisture on kinetics of  $\text{NO}_x$ , CO, and UHC production
- u Evaluation of stability limits of combustion with highly humid air

# Fundamental Data Base Generation - Program Tasks

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- u Modify combustors and flow systems to include steam injection
- u Baseline tests to evaluate operating limits (premixed vs diffusion flame burner)
- u Detailed experiments to determine effects of T, P, fuel type, and [H<sub>2</sub>O] on emissions
- u Input to design of sector test injector

# Fundamental Data Base Generation - Progress to Date

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- u Premixed flat flame combustor facility operated up to 60 atm
- u Data indicate uniform flame profile but heat loss to burner varies with pressure, affecting emissions
- u The premixed burner does not appear to be a viable test apparatus for controlled experiments with moist air

# Fundamental Data Base Generation - Progress to Date continued

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- u High temperature partially premixed burner facility operated up to 30 atm with inlet air preheated to 700K (800F)
- u Turbulent partially premixed flame data indicate present burner design not sufficient for stable operation at lean equivalence ratios with and without water addition

# Fundamental Data Base Generation - Progress to Date continued

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- u Steam generator and precision metered injection system developed and tested in high temperature facility at pressures up to 30 atm
- u Initial testing with present burner design indicate very unstable operation with water addition

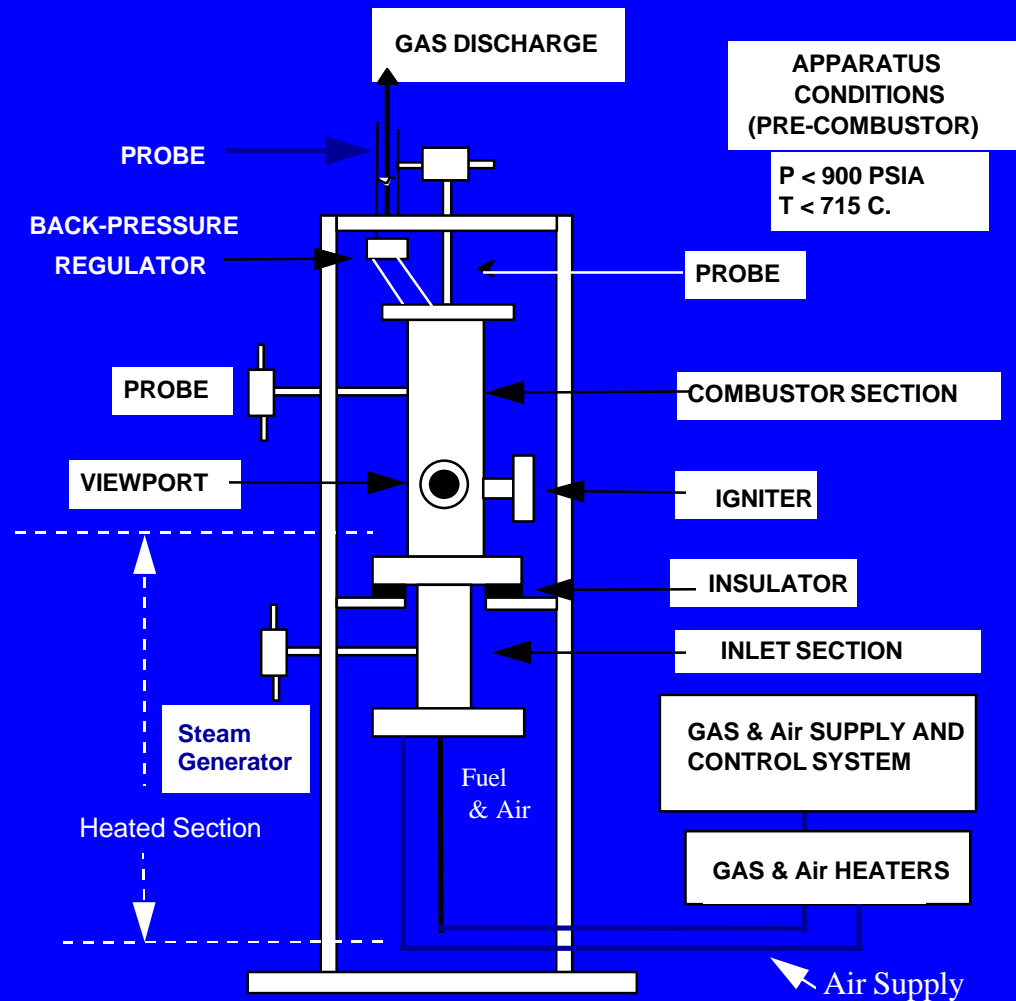
# Chemical Kinetic Code

## Development Progress to Date

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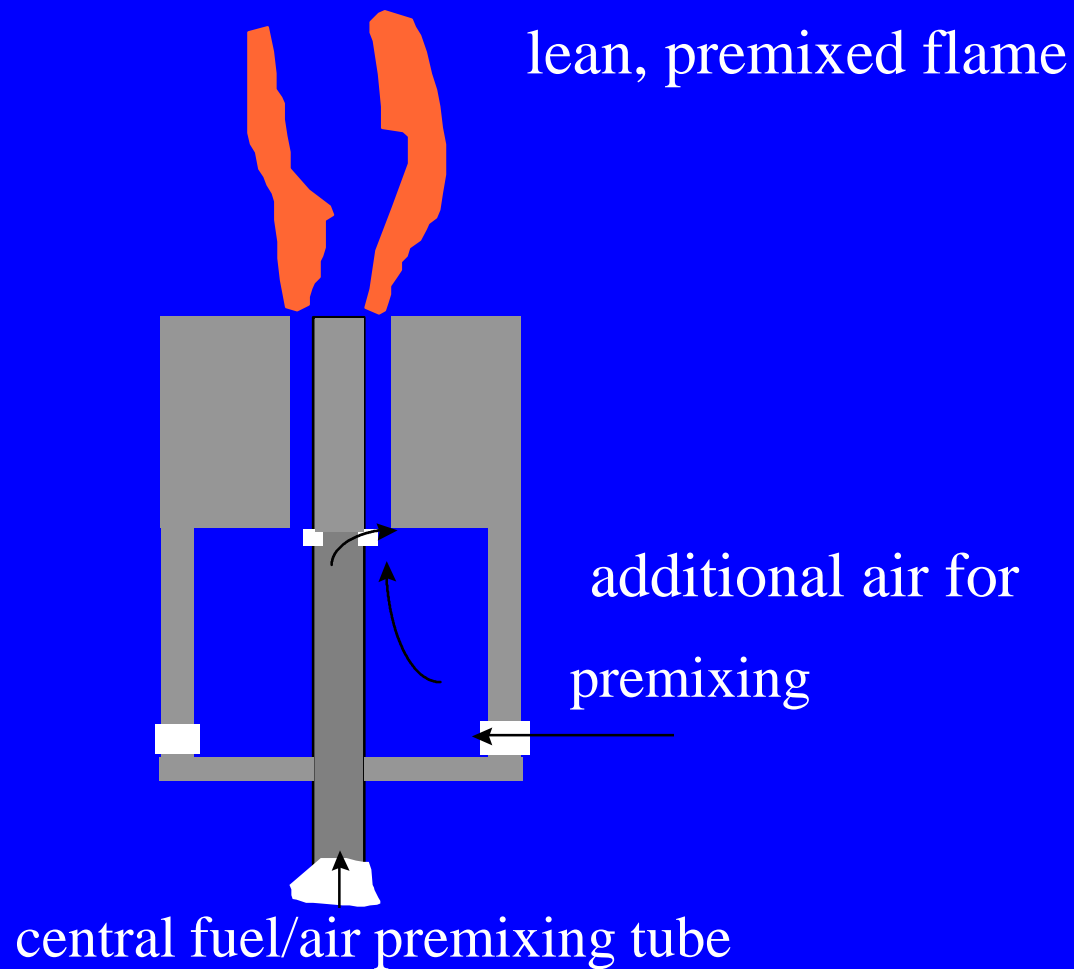
- u  $\text{NO}_x$  emissions as a function of flame temperature predicted using modified CHEMKIN II codes and GRIMECH2.11 for a perfectly premixed flame
- u Equilibrium flame temperature predicted for various flame equivalence ratios at each pressure level and equivalence ratio tested

# Schematic of High Pressure, High Temperature Combustion Facility



# Premixer and Flame Support

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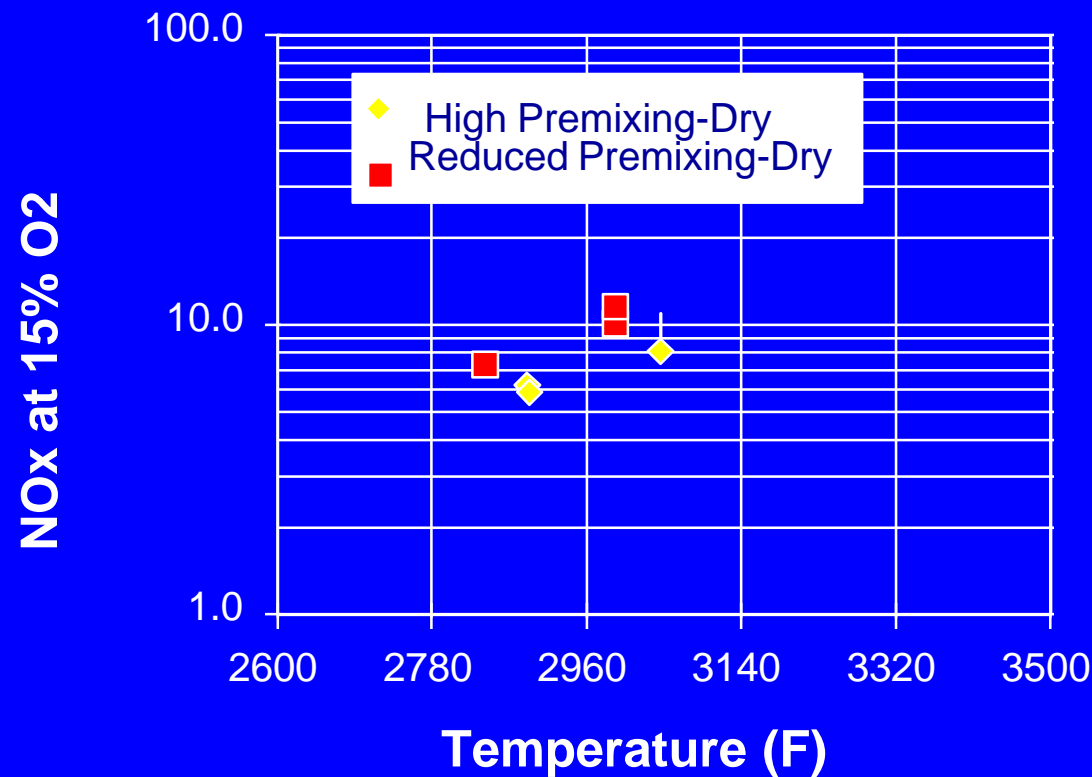
# Premixer Data Acquisition

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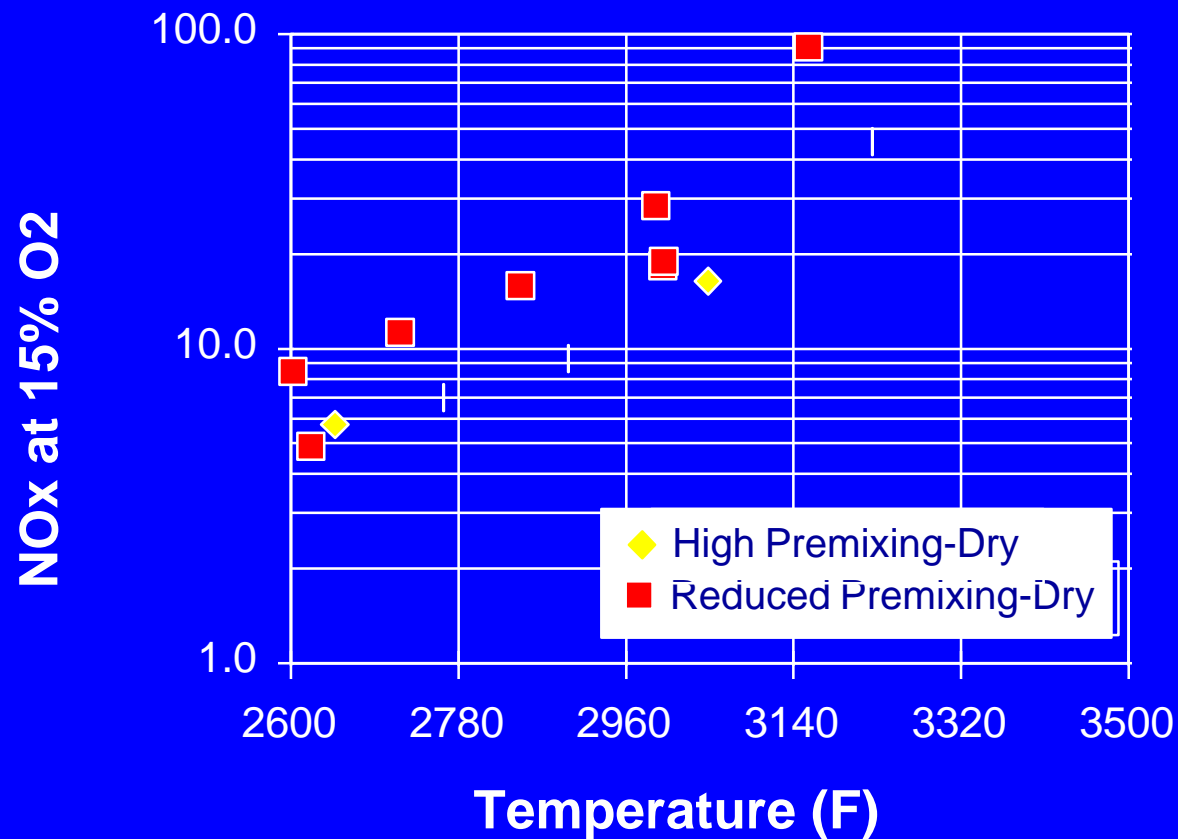
- u Data acquired at 10, 20, and 30 atm with inlet temperature of 700K (800F) with different ratios of air in central premixing tube to secondary air swirling around tube
- u This configuration allows parametric study of the effects of premixing on flame stability and emissions

# NO<sub>x</sub> Emissions as Function of Flame Temperature at 10 atm

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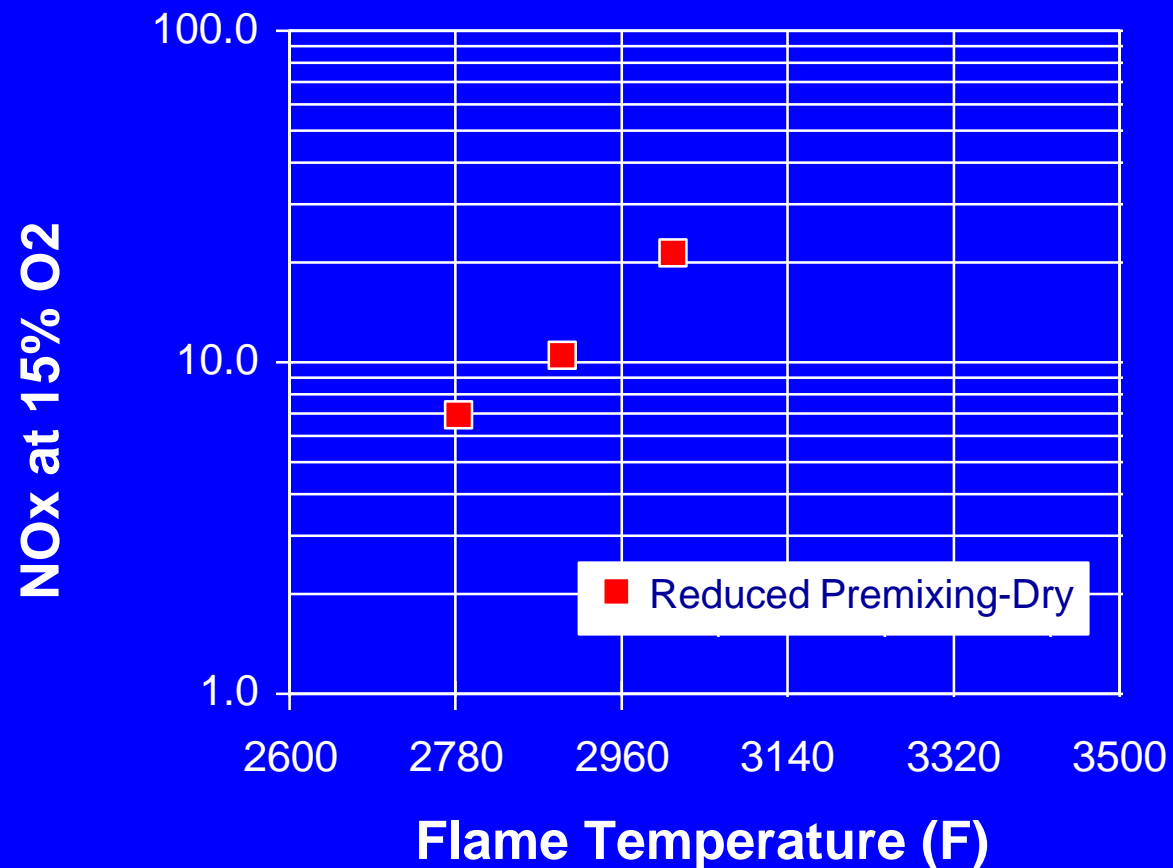


# NO<sub>x</sub> Emissions as Function of Flame Temperature at 20 atm

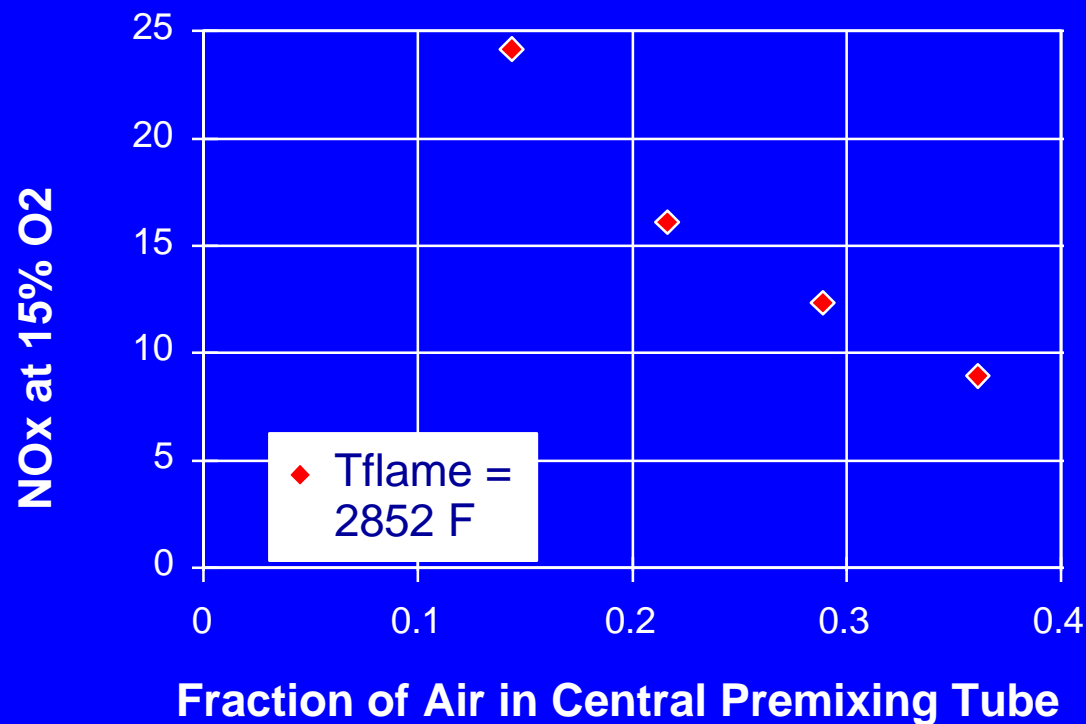


# NO<sub>x</sub> Emissions as Function of Flame Temperature at 30 atm

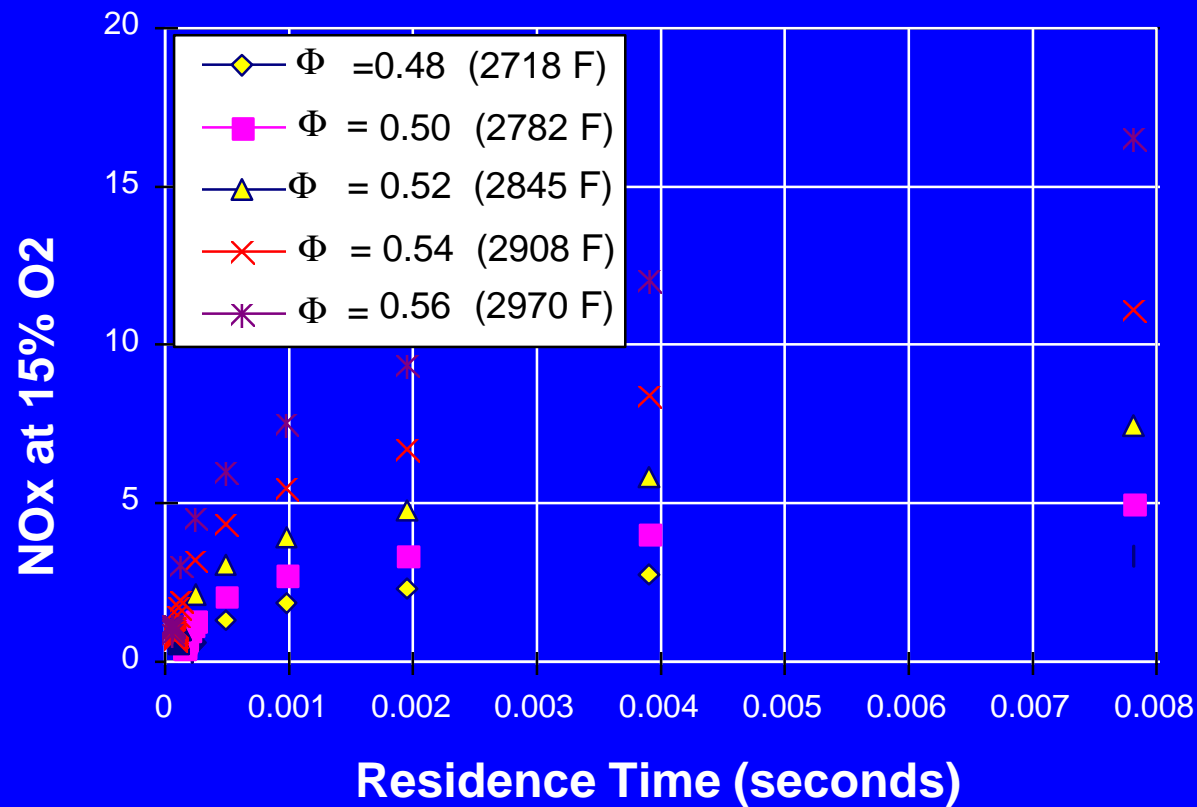
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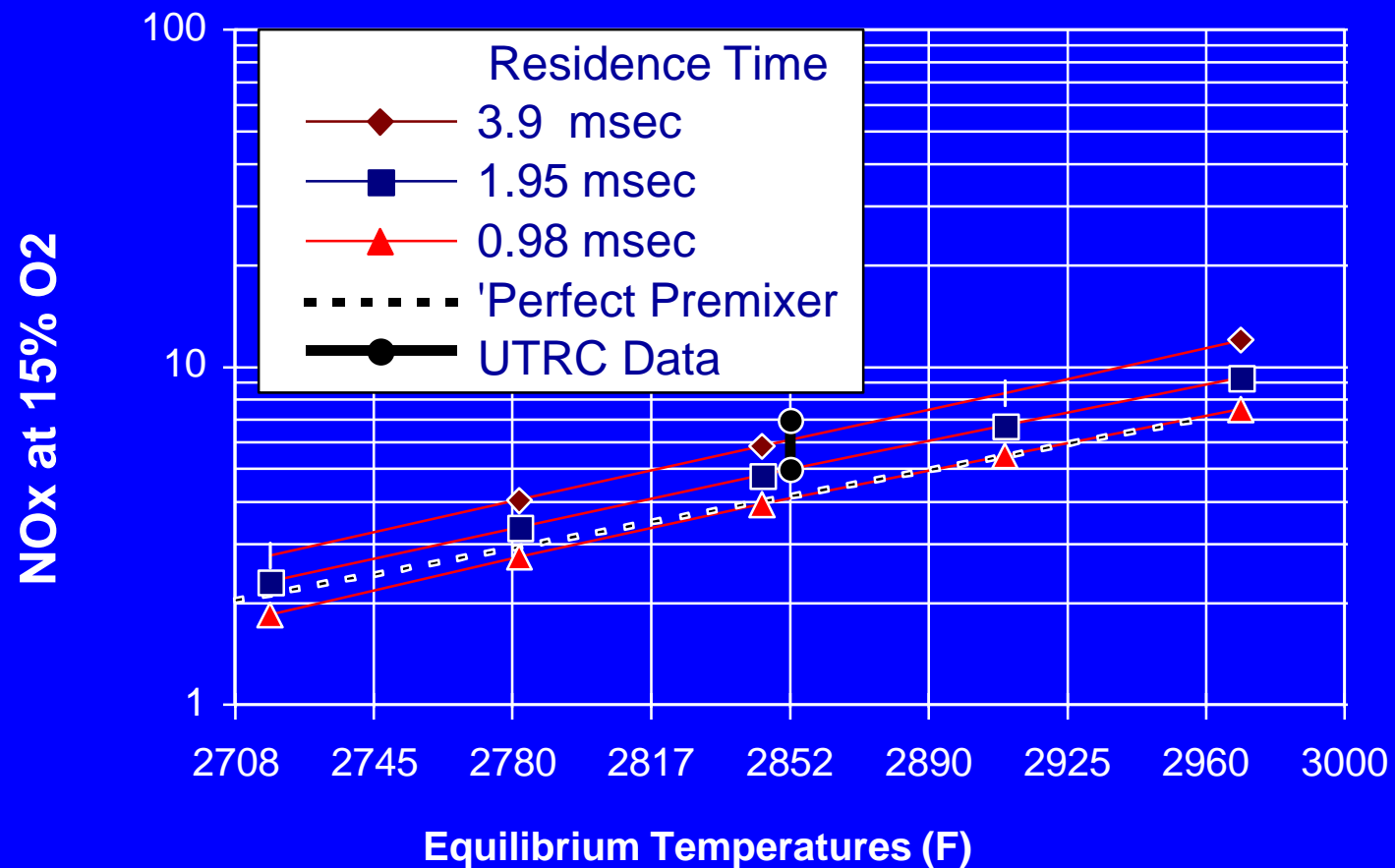
# Effect of Premixing on $\text{NO}_x$ Levels at 20 Atm



# *NO<sub>x</sub> Production in PSR at 20 atm (GRIMECH2.11)*



# NO<sub>x</sub> Predictions in PSR and Data vs. Flame Temperature



# Task 201 Planned Tasks

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- u Design, fabricate, and install new turbulent premixed burner which has improved premixing and stability characteristics over present burner design
- u Predict operating regime under high moisture levels as a function of equivalence ratio and flow velocities using modified kinetics codes

# Task 201 Program Schedule

